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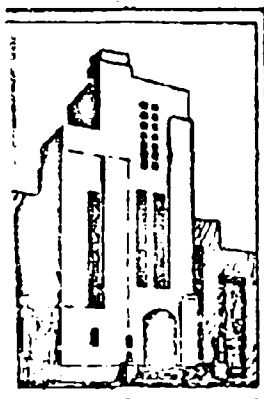


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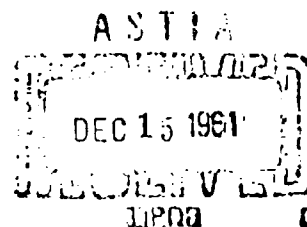
APPLIED
MATHEMATICS

THE EFFECTS OF AUSTENITIZING AND TEMPERING ON THE
MECHANICAL PROPERTIES OF FULLY QUENCHED HY-80 STEELS

by

A.R. Willner and M.L. Salive

XEROX



STRUCTURAL MECHANICS LABORATORY
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ABSTRACT

The effects of austenitizing, tempering temperatures and tempering times on fully quenched low- and high-chemistry HY-80 steels have been investigated. Correlation procedures have been established for relating notch-brittleness properties to tensile strength for a given Charpy V-notch fibrous fracture appearance. The results indicate that Charpy V-notch transition temperatures increase with increasing austenitizing and decreasing tempering temperatures. For fully quenched HY-80 steels, the optimum Charpy V-notch impact fibrous transition temperatures are attained for the 100,000-psi-yield-strength level.

INTRODUCTION

At the end of World War II the Bureau of Ships recognized the need for the development of a high-yield-strength steel to increase the combat effectiveness of submarines. To fulfill this need an investigation was initiated with the United States Steel Company and the International Nickel Company to develop a nonballistic, weldable, structural steel with a minimum yield strength of 80,000 psi in the water-quenched and tempered condition. Although this material, commonly known as HY-80, has been in use since 1951, little is known of its metallurgical properties. Therefore, a program^{1, 2} was established to perform metallurgical studies on isothermal transformation products, variations in chemistry, and impurities to determine their relation to the properties and weldability of high-strength steels. This program is concentrated on HY-80 steel, Military Specification MIL-S-16216.³ HY-80 steel is one of the family of nickel-chromium-molybdenum steels used in construction requiring high strength and notch toughness. The data obtained from this investigation can be used to prognosticate the effects of the variables studied on the mechanical properties of this family of steels.

The essential phases in this program are outlined in Figure 1. At the present time most of the experimental work for Phase I, Metallurgical Reactions, has been completed. It is apparent that a single report on the data compiled and the interpretation thereof would be prohibitively voluminous. Hence, Phase I will be subdivided into several reports. The detailed steps in Phase I are depicted in Figure 2.

This report, the first of the proposed series on Phase I, describes the effects of austenitizing and tempering on the mechanical properties of fully quenched HY-80 steels. The steps reported herein are those included within the broken line in Figure 2.

MATERIALS

The metallurgical principles governing the development of the weldable 80,000-psi-yield-strength structural steels were the same as those set forth by the Ad Hoc Committee

¹References are listed on page 56.

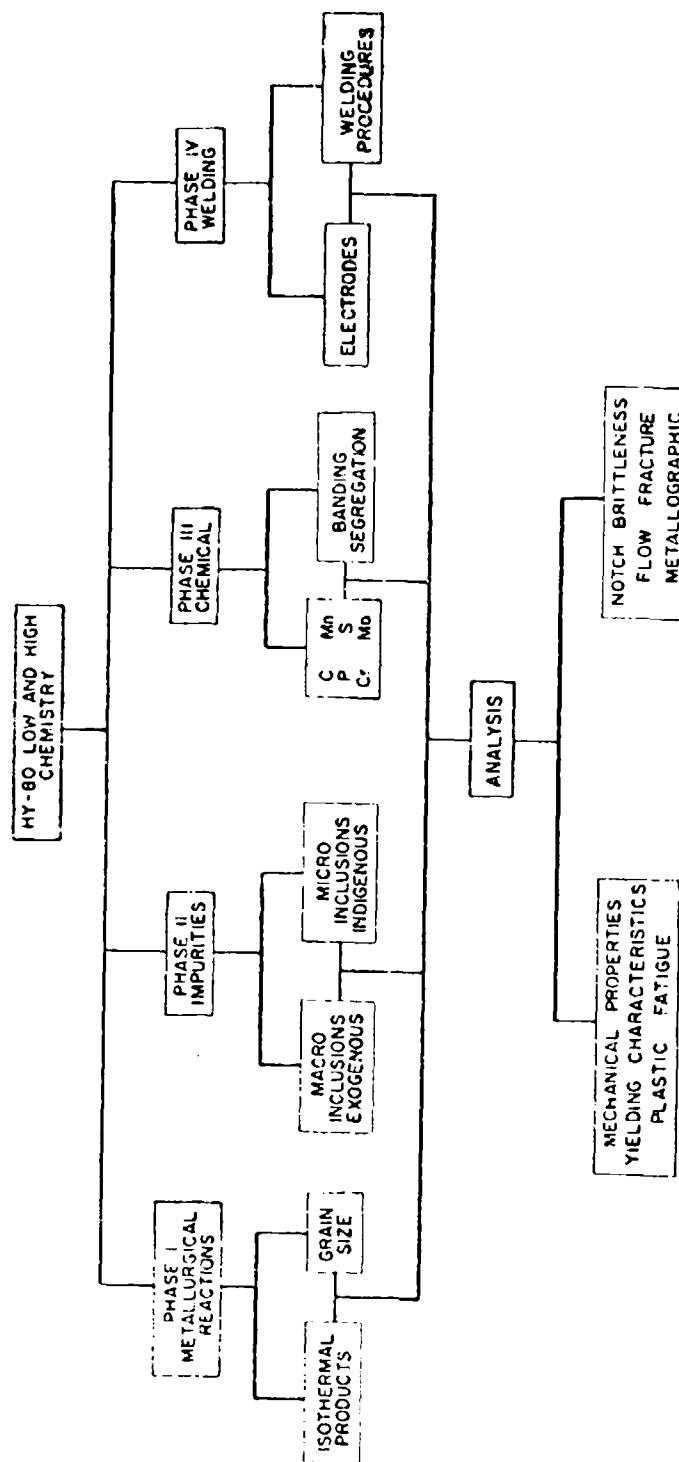


Figure 1 - Investigative Steps in the Study of HY-80 Steels

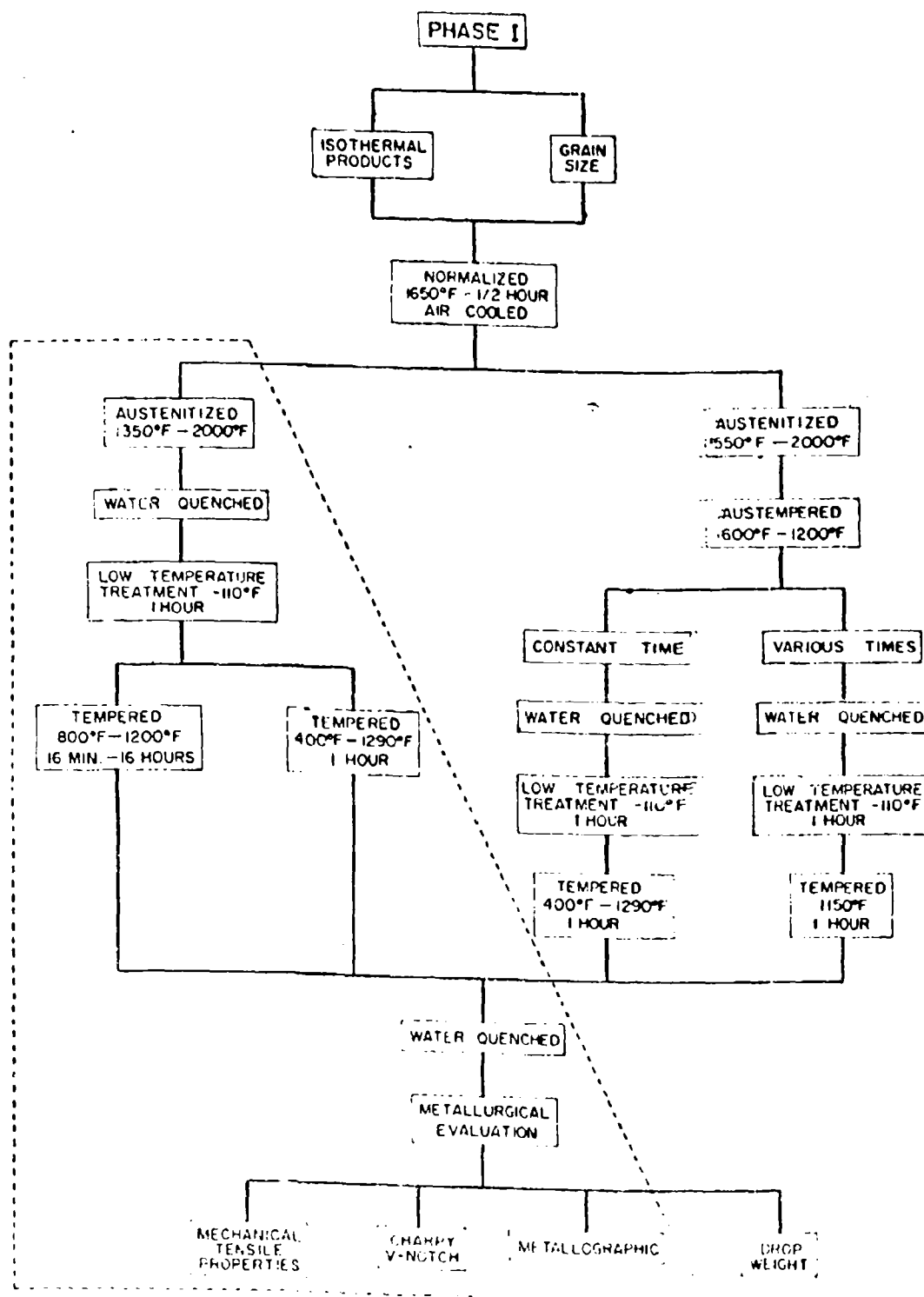


Figure 2 - Investigative Steps in the Study of Metallurgical Reactions of HY-80 Steels (Phase I)

on Naval Armor.⁴ One of the main requisites for development of the steel was that the steel selected must harden to a minimum of 80-percent martensite at the center of the plate after being quenched in still water. The committee based the 80-percent minimum requirement on available test data taken from armor plates, that is, the committee felt that the mechanical properties of a quenched and tempered steel would be detrimentally affected by increasing amounts of tempered nonmartensitic products.

Both a low-chemistry and a high-chemistry HY-80 steel were used in the study reported here. The low-chemistry, 1.2-in. plate was obtained from standard Navy stock. Unfortunately, the manufacturer's heat and plate numbers were partially obliterated in transportation. The identifying numbers which were visible indicated that the plate was manufactured by the U.S. Steel Corporation, Homestead Plant. At the start of this investigation, 1.2-in., high-chemistry, HY-80 plate was not a standard production item; however, U.S. Steel, Homestead Plant, contributed a 1.2-in. by 3-ft by 3-ft piece of high-chemistry, production-run plate left over from one of their experimental studies. These two plates were used throughout this investigation.

Although the high-chemistry plate was not a standard item, it was made from a standard open-hearth cast and rolled to thickness using the same production procedures normally used in manufacturing 1.2-in. plate. A thicker production plate would have added a chemical heterogeneity variable. Hence it is concluded that the test results obtained are indicative of the performance of high-chemistry commercially produced HY-80 plates.

CHEMISTRY

The chemistries of the HY-80 steels used in this investigation are compared in Table 1 with the specification requirements for HY-80.

The percentages of chemical impurities present in the test plates are believed such that their effects on maximum energy and transition temperatures and, therefore, on notch brittleness, would be negligible. Schwartzbart⁵ demonstrated that the Charpy V-notch transition temperature for steels containing 0.014 to 0.023 percent phosphorus is minimized if the Mo/P ratio is 5 or greater. Extrapolating Hodge's⁶ work for steels containing sulphur in the range of 0.011 to 0.018 percent showed that there was only a drop in maximum energy of 2 to 5 ft-lb and that sulphur content does not affect transition temperatures. Gregg,⁷ in reporting the work of others, showed that the impact properties of alloy steels containing nickel and chromium are not adversely affected by copper content below 0.25 percent. In general, the literature^{7, 8, 9} indicates that a small percentage of copper is beneficial.

TABLE 1

Comparison of Chemistries of Steels Used in This Investigation With Chemical Requirements of HY-80 Specification (MIL-S-16216D)

| Steel HY-80 | Chemistry, Percent | | | | | | | | |
|---|--------------------|-----------|---------|--------|-----------|-----------|-----------|-----------|------|
| | C | Mn | P | S | Si | Ni | Cr | Mo | Cu |
| Experimental | | | | | | | | | |
| Low Chemistry | 0.14 | 0.28 | 0.010 | 0.018 | 0.18 | 2.18 | 0.87* | 0.21* | 0.03 |
| High Chemistry | 0.15 | 0.24 | 0.011 | 0.014 | 0.14* | 2.85 | 1.44 | 0.45 | 0.03 |
| Specification Requirement | | | | | | | | | |
| Plate up to 56.1 psf | 0.22** | 0.10-0.40 | 0.035** | 0.04** | 0.15-0.35 | 2.00-2.75 | 0.90-1.40 | 0.23-0.35 | - |
| Plate above 51.0 psf | 0.23** | 0.10-0.40 | 0.035** | 0.04** | 0.15-0.35 | 2.50-3.25 | 1.35-1.85 | 0.30-0.60 | - |
| <p>* In check analysis variation of the specified limits is permitted by the following amounts: Si ± 0.03 Cr ± 0.06 Mo ± 0.03</p> <p>** Maximum percentage permitted.</p> | | | | | | | | | |

HARDENABILITY

The ideal critical diameter $D_{I,50}$ * or hardenability of these plates was calculated by the Grossman and Fields method.¹⁰ The equations developed by the Ad Hoc Committee on Naval Armor⁴ were used for converting the $D_{I,50}$ values to equivalent thicknesses L_{eq} of plates quenched in still water. Their hardenability conversion curves are reproduced in Figure 3 which converts $D_{I,50}$ values to 50-, 80-, and 95-percent martensite at center thickness for plates quenched in still water.

The D_I and L_{eq} values for 50-, 80-, and 95-percent martensite are listed in Table 2 where the hardenability characteristics for Grain Size 8 of the steel chemistries used in this investigation are compared with hardenability of the minimum and maximum chemistries of the HY-80 steel specification.

The tabulated D_I and L_{eq} values in Table 2 indicate that there are distinct differences in hardenabilities between the low- and high-chemistry HY-80 steels used in this investigation.

* Grossman's factors for obtaining $D_{I,50}$ are based on a 50-percent martensitic structure at the center of a round bar after an ideal quench.

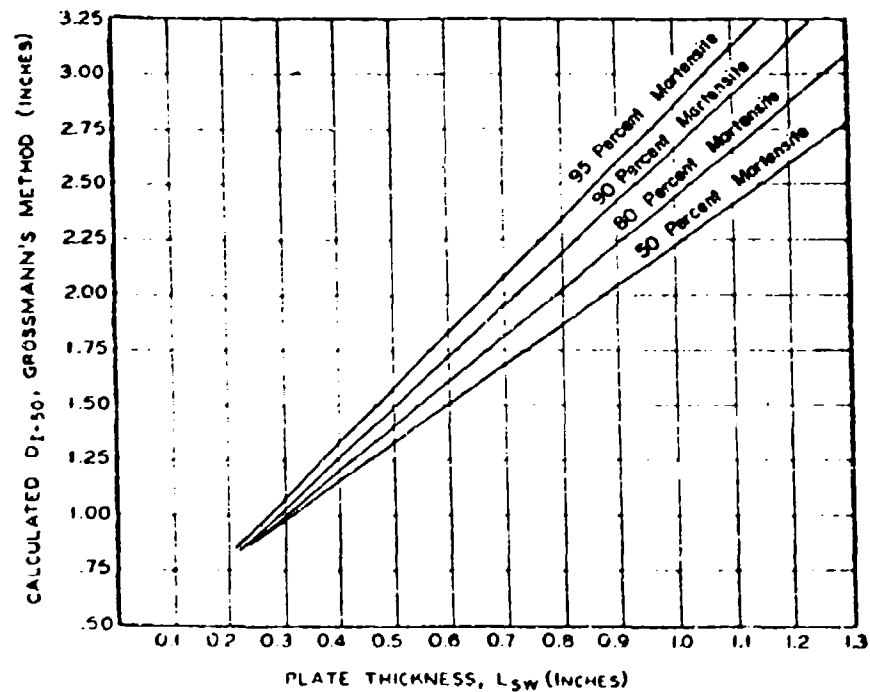
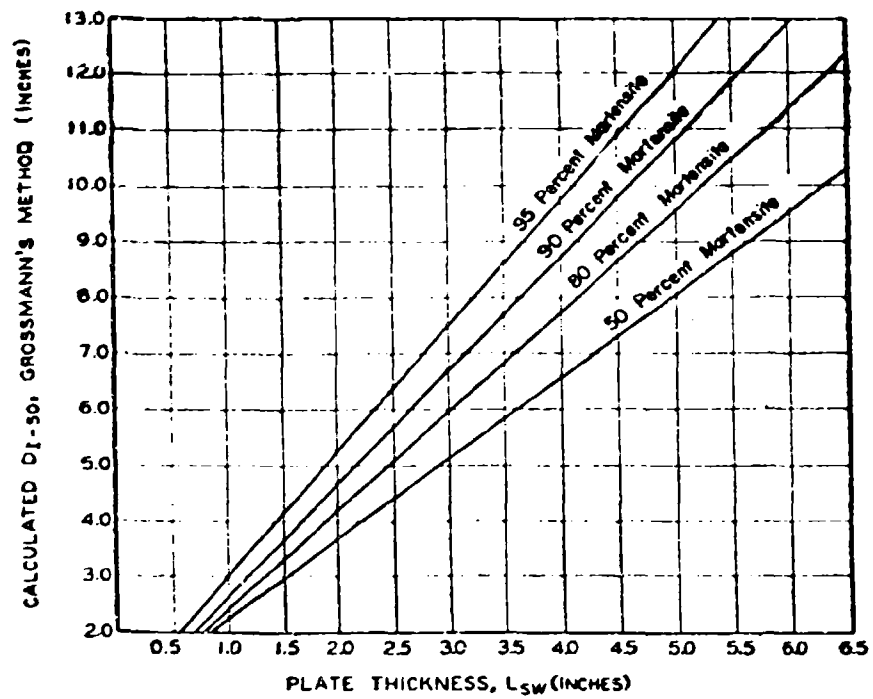


Figure 3 -- Conversion of Ideal Critical Diameter, D_{I-50} , to the Plate Thickness That Will Quench Out in Still Water, L_{SW} , with Various Percentages of Martensite

TABLE 2

Comparison of Calculated Hardenabilities of the Steels Used in This Investigation with the Hardenabilities of Minimum and Maximum Chemistries of HY-80 Specification (MIL-S-16218D)

| Steel | Critical Diameters,* in. | | | Plate Thickness (Still Water Quench), in. | | |
|----------------------|--------------------------|------------|------------|---|-------------|-------------|
| | D_{I-50} | D_{I-80} | D_{I-95} | L_{su-50} | L_{su-80} | L_{su-95} |
| Experimental | | | | | | |
| Low Chemistry | 2.25 | 1.66 | 1.03 | 0.96 | 0.89 | 0.75 |
| High Chemistry | 5.52 | 4.34 | 3.03 | 3.25 | 2.75 | 2.16 |
| Specification | | | | | | |
| Plate up to 56.1 psi | | | | | | |
| Low Range | 1.42 | 0.98 | 0.53 | 0.58 | 0.52 | 0.45 |
| High Range | 8.00 | 6.38 | 4.54 | 4.96 | 4.18 | 3.31 |
| Plate above 51.0 psi | | | | | | |
| Low Range | 2.68 | 2.02 | 1.29 | 1.23 | 1.16 | 1.03 |
| High Range | 17.35 | 14.05 | 10.24 | 11.5 | 9.50 | 7.25 |
| * Grain Size 8 | | | | | | |

Because of the differences in hardenabilities, the test results obtained are considered indicative of the mechanical property behavior of both the low- and high-chemistry HY-80 steels.

CRITICAL POINTS

Ideal critical equilibrium points A_{c1} and A_{c3} were calculated using the method developed by Lambert and Grange.¹¹ Dilatometric critical temperature measurements A_{c1} and A_{c3} were made at the Naval Weapons Plant, Washington, D.C. The calculated critical equilibrium points and the dilatometric critical temperature measurements are compiled in Table 3. The differences between the A_c' and the A_c values are those which would be expected when ideal equilibrium points are compared with the actual critical transformation temperatures obtained during heating.

TEST SPECIMENS

To remove the effects of any previous heat-treatment, the as-received stock was normalized at 1650°F and then tempered at 1200°F. All heat-treatments were performed in neutral salt-bath furnaces with temperatures controlled to within $\pm 5^\circ\text{F}$.

TABLE 3

Calculated and Measured Critical Temperatures of Low- and High-Chemistry
HY-80 Steels Used in This Investigation

| | Critical Points, $^{\circ}\text{F}$ | | | |
|----------------|-------------------------------------|----------|----------|----------|
| | Calculated | | Measured | |
| HY-80 | A_{c1} | A_{c3} | A_{c1} | A_{c3} |
| Low Chemistry | 1313 | 1483 | 1360 | 1550 |
| High Chemistry | 1321 | 1483 | 1320 | 1470 |

For each heat-treating variable to be studied, a set of specimens, comprising two or more tensile specimens and a minimum of nine impact specimens, were heat-treated at one time. Specimens in each set were taken at random locations across the plate. Thus, if any unrelated localized imperfection in the plate were present, it would not be evident in the final test result.

Prior to final austenitizing heat-treatment, the tensile and Charpy V-notch impact specimens were rough-machined equally from the surfaces of the plate to within 0.02 in. of final dimensions. Metallographic analysis indicated that the as-quenched specimen contained 3- to 5-percent retained austenite. After the specimen was held in a mixture of dry ice and acetone at -110°F for 1 hr, the retained austenite transformed into martensite, that is, examination at a magnification of 1500 X indicated that the transformation of the visible retained austenite was complete. All specimens were given a low-temperature quench immediately after the brine quench to facilitate the transformation of retained austenite to martensite.

Specimens which were austenitized above 1700°F were transferred to a salt bath whose temperature was 1550°F for the low-chemistry steel and 1625°F for the high-chemistry steel. This procedure eliminated any questionable results which might have arisen because of differences in thermal gradients between the austenitizing temperature and the brine quench and duplicated possible hot spots which may occur in any production type of a continuous heat-treating zone furnace.

For all austenitizing treatments, almost all the specimens were held for 1/2 hr at temperature prior to quenching. After quenching, the specimens were held at the tempering temperature for prescribed times, and then water quenched.

After final heat-treatment, standard-threaded, 0.252-in.-diameter, tensile specimens and standard Charpy V-notch specimens (notched perpendicular to the rolled surface through the thickness of the plate) were machined in accordance with Federal standards 2.2, 13.

In order to obtain the best test results from the studies of metallurgical reactions, it was felt that the test specimens had to be taken in such orientation with respect to plate rolling as to minimize the effects of possible chemical banding and the effects of directional nonmetallic inclusions. These variables, if present, run parallel to the direction of major

plate roll in discrete layers. These defects, if present in a transverse tensile specimen, would act as points of weakness. In longitudinal, Charpy V-notch impact specimens, these defects would be perpendicular to the direction of crack propagation and would, therefore, it is believed, act partially as crack arresters.

To prevent any of these extraneous defects from masking the results of the variables being studied, the tensile specimens were machined parallel to the direction of major plate roll, and the Charpy V-notch impact specimens from the transverse direction, so that if banding or nonmetallic inclusions were present within the test specimen, they would be distributed as dispersed particles. Since the low-chemistry HY-60 steel plate was plentiful, several transverse tensile and longitudinal impact specimens were made to investigate the effects of directionality on the heat-treated specimens. Because of the scarcity of high-chemistry HY-60 material, only a few longitudinal Charpy V-notch impact specimens were made from this plate for comparison. It is to be noted that the effects of chemical banding and the directional inclusions on mechanical properties and notch brittleness will be studied in the second and third phases of this investigation.

EXPERIMENTAL PROCEDURES

The experiments included tensile and Charpy V-notch impact tests and extensive metallographic analyses of all resultant microstructures.

MECHANICAL TESTS

Mechanical property load-strain curves were recorded by an automatic Baldwin-Southwark microformer load-strain recorder attached to a 20,000-lb hydraulic testing machine. A strain magnification of 500 to 1 was used throughout this investigation. In order to avoid any eccentric loading, universal-joint threaded gripping devices were employed.

Charpy V-notch impact specimens were tested in a Tinius-Olsen, pendulum-type impact tester with a capacity of 265 ft-lb and a striking velocity of 16.85 fps. Prior to testing, the machine was calibrated in accordance with ASTM standards.¹⁴ Federal standard procedures^{12, 13} were used for testing both the tensile and Charpy V-notch impact specimens.

Percent fibrous fractures and lateral expansions were calculated from measurements obtained from the broken impact specimens. Percent Charpy V-notch fibrous fractures were obtained at a magnification of 300X using a micrometer eyepiece. These measurements were checked a number of times, and the results always agreed within 2 or 3 percent. The most difficult percent fiber to determine was the fiber of specimens tempered from 400 to 600°F. For each tempering temperature fracture appearance was established by observing the difference between the appearance of these specimens and the appearance of the specimens for which maximum and minimum energies were recorded. Lateral expansions were measured at the point of impact on the compression side of the broken impact specimen.

METALLOGRAPHY

Metallographic specimens were mounted in transapic mounting resin. After the specimens were mounted, 1/16 inch of specimen surface was machined off under coolant. The surfaces were then progressively ground by hand on 180-, 240-, 400-, and 600-grit silicon carbide papers. Final polishing was performed in two stages utilizing a 60-cycle automatic vibrating polisher. In the semifinal polishing, the bowl mounting plate was covered with a bleached silk cloth and a slurry of Liscle W, distilled water, and aerosol. (Gama) cloth covered with a slurry of Liscle B, distilled water, and aerosol was used for the final polishing operation.

An ethereal picric acid containing Zephiran Chloride^{15*} was used to reveal the prior austenitic grain boundaries and temper embrittlement. Three etchants were used to reveal the microstructures of the as-quenched and tempered specimens: a solution of saturated picric acid for delineating grain boundaries; a 1-percent nital solution for etching the ferrite; and a 20-percent water solution of anhydrous sodium metabisulfite for staining the as-quenched and tempered martensites. Between each etching the specimens were washed and dried.

Austenitic micrograin size measurements were taken in accordance with ASTM standards.¹⁶

TEST RESULTS

In Tables 4 through 7 the mechanical properties of the various quenched and tempered heat-treatments investigated are given. Figures 5 through 28 depict the mechanical properties and notch brittleness¹⁷ data in various combinations. It is realized that the data could be presented in many other combinations, but the plots given are believed to be significant.

The Charpy V-notch curves, such as energy absorbed versus testing temperatures, are point-to-point plots of the test results; however, for correlation of data least-square fits were made. The best least-square fit was found by selecting the fit which gave the minimum residual.

Yielding characteristics, i.e., the shape of the stress-strain curve, are reported as one of the factors which shows sensitivity to heat-treating. This factor was selected based upon previous work performed at the Model Basin which related the effects of yielding characteristics to heat-treatment.^{17, 18}

Notch brittleness is used throughout this report to define the effects of various metallurgical factors on the energy absorption, fracture appearance, and lateral expansion characteristics for a given test temperature. Arbitrary standards for notch brittleness of 100-, 60-, 50-, and 30-percent Charpy V-notch fibrous fracture characteristics have been chosen. Charpy V-notch impact fibrous fracture transition temperatures are reported as the temperature at which a given fibrous appearance is ascertained.

* Zephiran Chloride is the registered trade name of a brand of benzalkonium chloride manufactured by Winthrop-Strains, New York 18, New York.

** Notch brittleness is the susceptibility of a metal to fracture at points of stress concentration caused by a notch when subjected to suddenly applied load.

Lateral expansion is reported in the figures depicting Charpy V-notch properties. These data are presented here but not discussed.*

EFFECTS OF AUSTENITIZING TEMPERATURES

To investigate the effects of austenitizing temperatures upon grain size and mechanical and notch-brittleness properties of HY-80 steels, specimens which had been tempered at 1150°F after quenching from the austenitizing treatment were studied. The 1150°F was chosen because it is the minimum tempering temperature required by the military HY-80 specification.³

Grain Size

Table 4 lists and Figures 4 and 5 depict the effects of austenitizing temperatures on the austenitic grain size. Grain size in low-chemistry HY-80 steels appears to increase progressively with increasing austenitizing temperatures. However, for the high-chemistry HY-80 steel, the microstructure becomes abnormal when austenitized at 1850°F. At the 2000°F austenitizing temperature, the grain size becomes somewhat uniform and equiaxed. However, the large grains of the abnormal structure (ASTM-3) are larger than the average austenitic grains obtained for the higher austenitizing temperatures (ASTM-5).

Tensile Properties

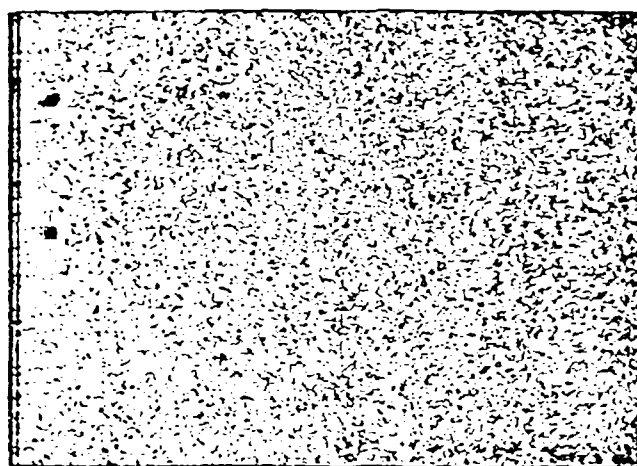
The effects of tempering at 1150°F after quenching from various austenitizing temperatures on the mechanical properties are also given in Table 4. The mechanical properties appear not to be affected until the 1800 to 1850°F austenitizing temperatures are reached; at these and higher temperatures, the mechanical properties are slightly lower.

Notch Brittleness

The results of the effects of tempering at 1150°F after quenching from the various austenitizing treatments on notch brittleness are presented in Table 4 and depicted in Figures 6 and 7. It is evident in Figure 6 that, for longitudinal Charpy V-notch impact specimens of low-chemistry HY-80 steel, the data show a definite increase in transition temperatures with increasing austenitizing temperatures. Although there is a juxtaposition of the transverse Charpy V-notch curves for both the low- and high-chemistry HY-80 as shown in Figures 6 and 7 for austenitizing temperatures of 1700°F and below and for 1800°F and above, there is a marked separation between the results obtained from the 1700 and 1800°F austenitizing treatments; see Figure 7.

*The relationship of Charpy V-notch energy absorption, fibrous fracture appearance, and lateral expansion to the drop weight all-ductility transition temperature (NDT) and heat-treatment will be discussed in a later report.

(Test continued on page 17.)



1550-1650°F

ASTM 10-11



1850°F

ASTM 6-3



2000°F

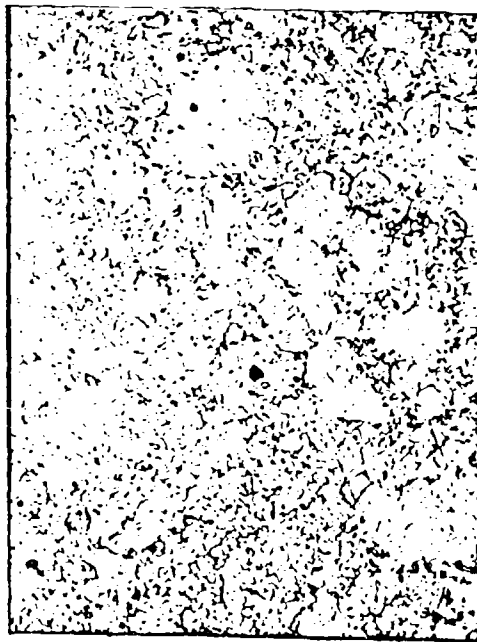
ASTM 5-4

Figure 4 - Photomicrographs at 100 X of Normal and Large Austenitic Grains of Low-Chemistry HY-80 Steel Austenitized as Indicated



1550-1700°F

ASTM 11



1850°F

ASTM 9-3



2000°F

ASTM 5-4

Figure 5 - Photomicrographs at 100 X of Normal, Anomalous, and Large Austenitic Grains of High-Chemistry HY-80 Steel Austenitized as Indicated

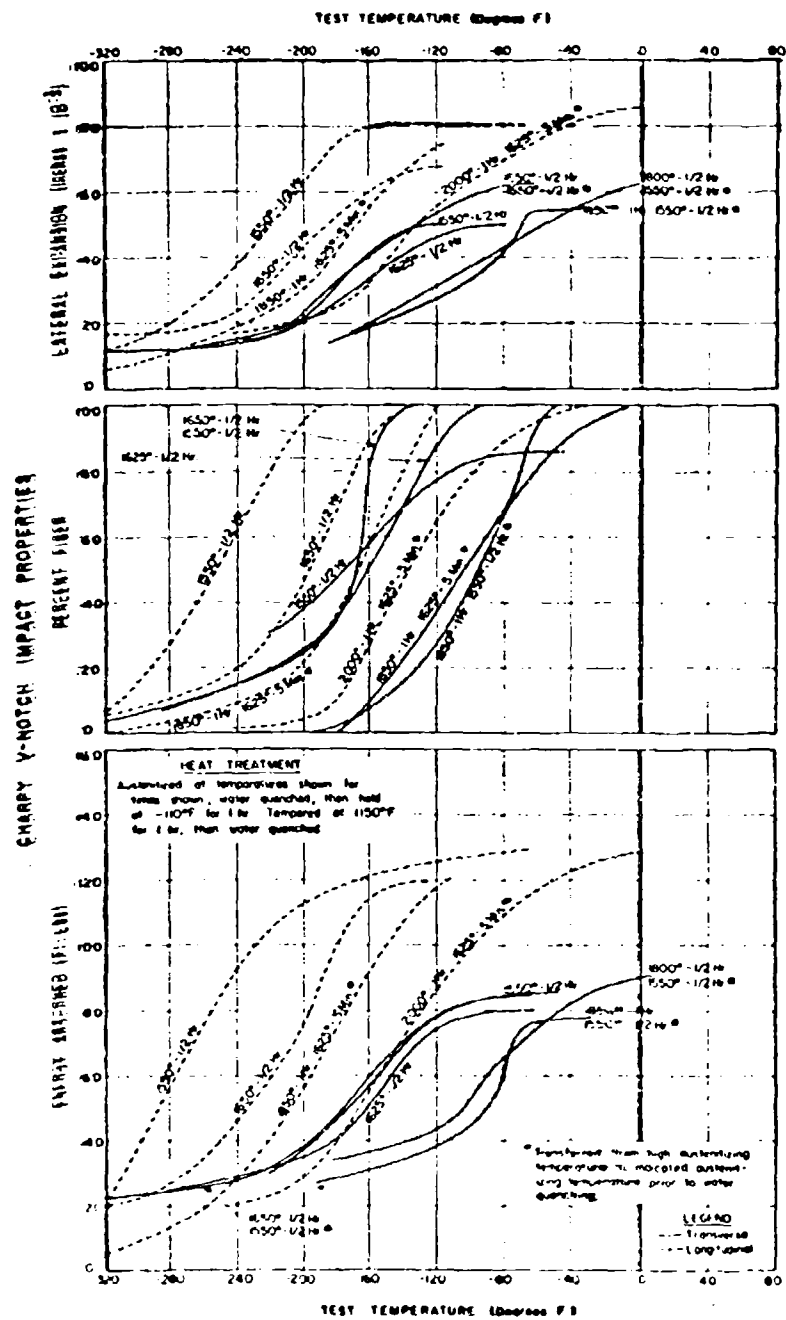


Figure 6 - Effects of Tempering at 1150°F on Charpy V-Notch Impact Properties of Low-Chemistry HY-80 Steels after Quenching from Various Austenitizing Temperatures

EFFECTS OF VARIOUS TEMPERING TEMPERATURES AFTER QUENCHING FROM VARIOUS AUSTENITIZING TREATMENTS

Varying tempering temperatures and austenitizing treatments were investigated to study their effects on mechanical properties such as tensile strength, yielding characteristics, and notch brittleness. Although the mechanical properties resulting from the tempering temperatures investigated fall outside of specification requirements, the results will be used as a basis for evaluating the other phases of this study to be reported separately.

Tensile Properties

After the specimens were quenched from the austenitic state, the tensile strengths, as expected, decreased with increasing tempering temperatures. However, Figure 8 shows that, for tempering temperatures below 1150°F, the mechanical tensile properties are higher for those specimens austenitized in the 1550 and 1625°F range than those austenitized at 2000°F. At the higher tempering temperatures, 1150 to 1250°F, the tensile properties approach each other.

The longitudinal and transverse tensile properties depicted in Figure 9 show that the longitudinal tensile data are higher than the transverse data for tempering temperatures below 900°F. Above 900°F the tensile data merge together. There is no reversal due to directionality in ductility, i.e., percent reduction in area and percent elongation, for any given tempering temperature. All the longitudinal percent-reduction-in-area data are approximately 10 percent higher than the transverse data. However, the percent elongation does not reflect any difference between the longitudinal and transverse directions.

From Tables 5 and 6 it can be seen that hardness, Rockwell C, is affected by austenitizing temperatures, that is, HY-80 steels tempered below 1000°F after quenching from high austenitizing temperatures have a lower hardness number than those austenitized at lower temperatures.

Yielding Characteristics

In general, the stress-strain curves for HY-80 steel austenitized at 1550 or 1625°F have similar yielding characteristics. It is shown in Figure 10 that the yielding behaviors of both low- and high-chemistry HY-80 steels are similar, that is, the low-chemistry HY-80 steel demonstrates a discontinuous yield for tempering temperatures of 500 and 600°F, whereas the high-chemistry steel shows a discontinuous yield for tempering temperatures of 600 and 800°F. The stress-strain curve for the high-chemistry HY-80 steel again becomes curvilinear at the 1000°F tempering temperatures. An upper yield point becomes perceptible after 900°F temper for the low-chemistry HY-80 steel; whereas, for the high-chemistry steel, the upper yield point is apparent after the 1200°F tempering temperature.

For the duplex 2000 to 1550°F and 2000 to 1625°F austenitizing treatments, the stress-strain curves for various tempering temperatures, Figure 10, show a curvilinear yield up to the tempering temperature of 1150°F; at 1200°F the curves have a plateau.

(Text continued on page 23.)

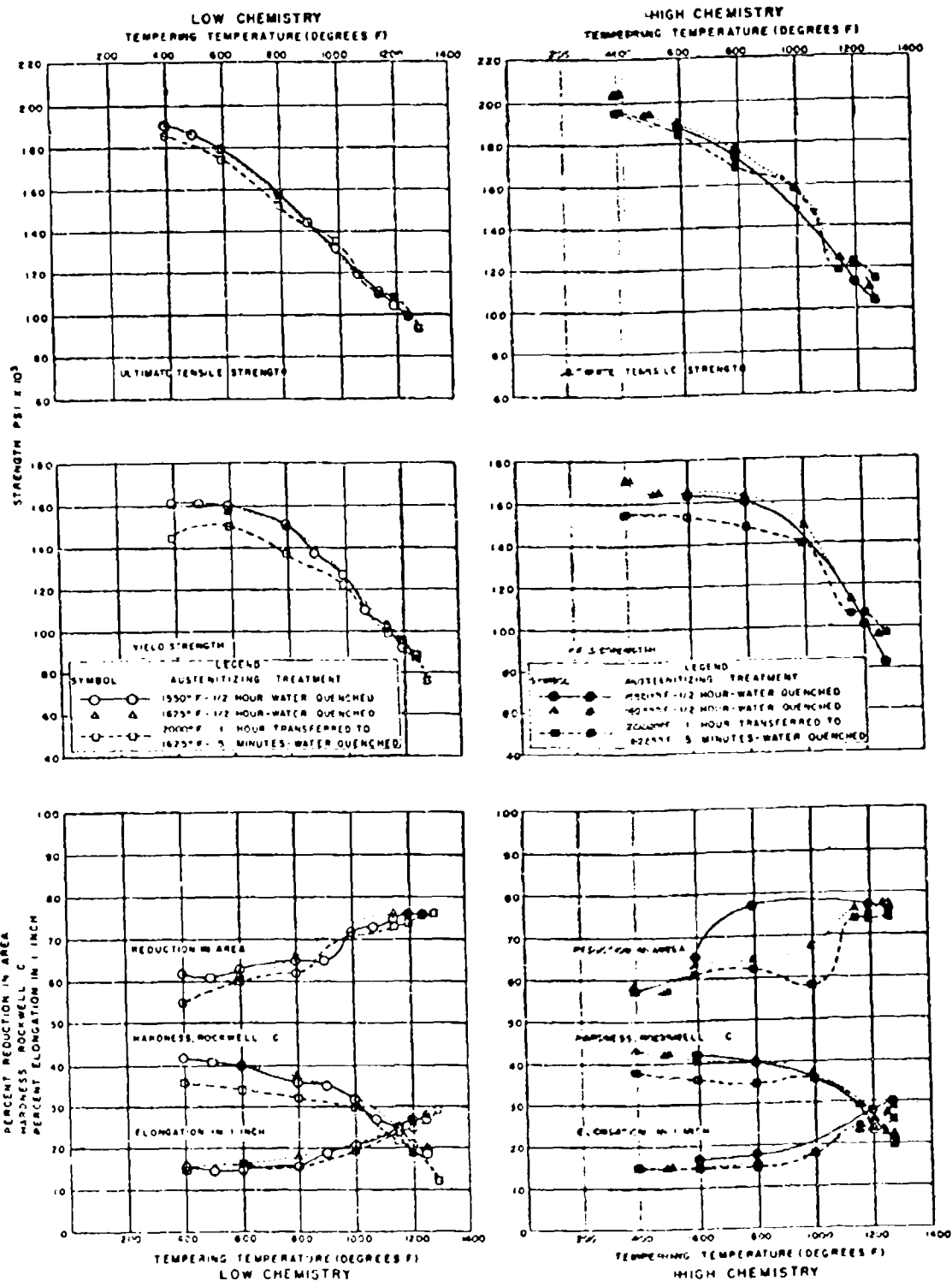


Figure 8 - Effects of Various Tempering Temperatures on Mechanical Properties of Low- and High-Chemistry HY-80 Steel after Quenching from Low and High Austenitizing Temperatures

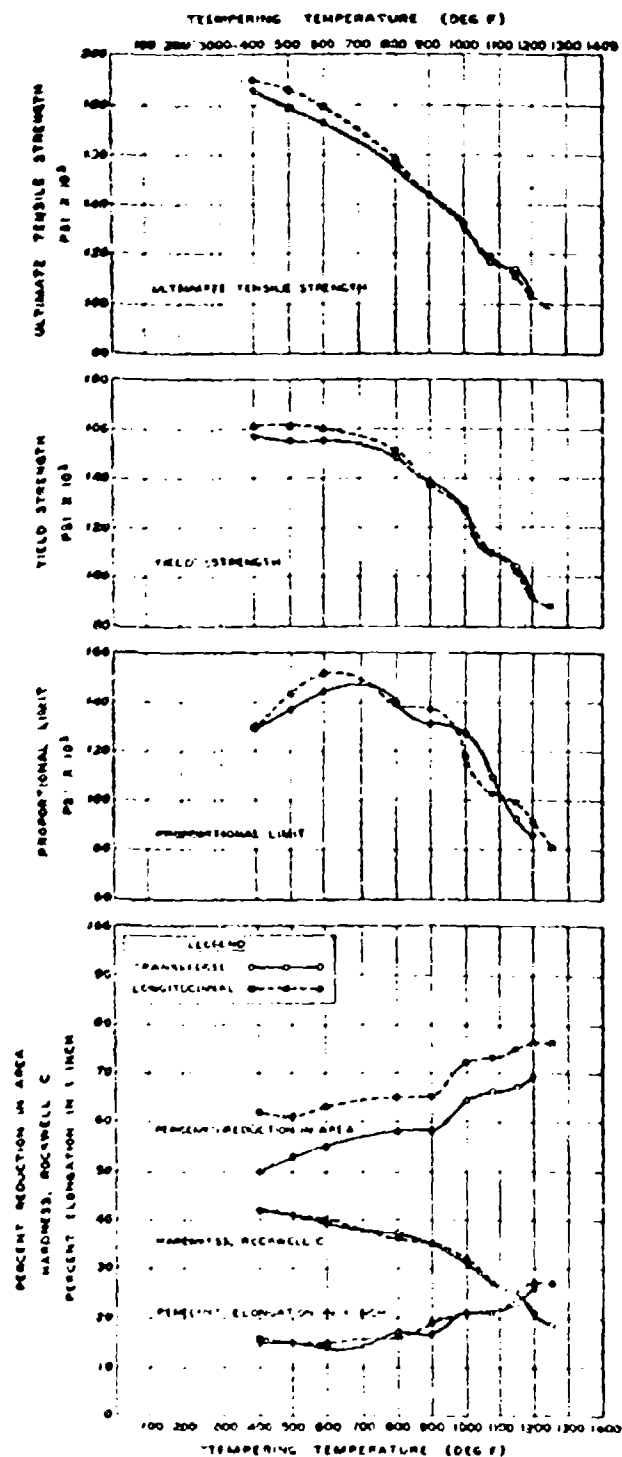


Figure 9 - Effects of Directionality on Mechanical Properties of Low-Chemistry HY-80 Steel

The steel was austenitized at 1550°F for 1/2 hour, water quenched, held at -110°F for 1 hour, tempered 1 hour as indicated, and then water quenched.



TABLE 5
Effects of Various Tempering Temperatures on Mechanical Properties of Low-Chemistry HY-80 Steel
after Quenching from Various Austenitizing Treatments

| Temperature | | ASTM Specimen Grain Size | Yield Strength ksi | Ultimate Tensile Strength ksi | Percent Reduction in Area | Percent Elongation in 1 inch | Ratio $\frac{P_{0.2}}{Y.S.}$ $\frac{T.S.}{Y.S.}$ | Hardness Rockwell C Scale | Roth Brittleness | | | | | | | | | |
|------------------------|-------------------|-----------------------------------|--------------------------|--|---------------------------------|------------------------------------|--|---------------------------------|----------------------------|---|-----------------|--|-----------------|--|-----------------|--|------|----|
| Austenitizing (°F) | Tempering (°F) | | | | | | | | Maximum Energy ft-lb | 100% Fibrous fracture Temp. deg F | Energy ft-lb | 10% Fibrous fracture Temp. deg F | Energy ft-lb | 50% Fibrous fracture Temp. deg F | Energy ft-lb | 20% Fibrous fracture Temp. deg F | | |
| LONGITUDINAL SPECIMENS | | | | | | | | | | | | | | | | | | |
| 1 | 6.0 | 11 | 129 | 161 | 62 | 16 | 80 | 85 | 42 | 44 | 76 | 41 | -4 | 41 | -27 | 39 | -112 | 34 |
| 1300 | 4.0 | 8 | 85 | 145 | 55 | 13 | 35 | 79 | 36 | - | - | - | - | - | - | - | - | - |
| | | | | | | | | | | | | | | | | | | |
| 1375 | 4.0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 1390 | 4.0 | 11 | 135 | 168 | 63 | 15 | 94 | 89 | 40 | 50 | 80 | 40 | 11 | 40 | -39 | 39 | -79 | 32 |
| 1400 | 4.0 | 16 | 146 | 179 | 61 | 16 | 93 | 88 | 40 | - | - | - | - | - | - | - | - | - |
| 1420 | 4.0 | 2 | 116 | 153 | 60 | 16 | 77 | 81 | 36 | 44 | 14 | 42 | -10 | 42 | -76 | 42 | -10 | 37 |
| 1450 | 4.0 | 11 | 139 | 151 | 65 | 16 | 92 | 96 | 36 | 44 | 14 | 42 | - | - | - | - | - | - |
| 1475 | 4.0 | 16 | 150 | 157 | 66 | 18 | 100 | 96 | 37 | - | - | - | - | - | - | - | - | - |
| 1500 | 4.0 | 16 | 137 | 152 | 62 | 16 | 81 | 90 | 32 | 42 | 10 | 37 | -22 | 65 | -106 | 40 | -179 | 40 |
| 1525 | 4.0 | 10.5 | 137 | 144 | 65 | 19 | 100 | 96 | 35 | 42 | - | - | - | - | - | - | - | - |
| 1550 | 4.0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 1575 | 4.0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 1590 | 4.0 | 11 | 118 | 127 | 72 | 21 | 93 | 96 | 32 | 46 | 32 | 32 | -119 | 68 | -163 | 32 | -179 | 46 |
| 1625 | 4.0 | 4 | 94 | 122 | 71 | 20 | 80 | 90 | 30 | - | - | - | - | - | - | - | - | - |
| 1650 | 4.0 | 11 | 133 | 119 | 73 | 21 | 96 | 93 | 27 | 121 | 78 | 119 | -166 | 94 | -191 | 77 | -217 | 90 |
| 1675 | 4.0 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 1700 | 4.0 | 11 | 99 | 125 | 75 | 25 | 97 | 93 | 25 | 129 | 115 | 117 | -270 | 104 | -254 | 80 | -277 | 90 |
| 1725 | 4.0 | 10 | 99 | 121 | 76 | 25 | 96 | 93 | 25 | 131 | 6 | 127 | -35 | 99 | -131 | 73 | -135 | 97 |
| 1750 | 4.0 | 4 | 85 | 99 | 73 | 26 | 86 | 84 | 27 | 131 | 6 | 127 | -100 | 100 | -212 | 60 | -235 | 61 |
| 1775 | 4.0 | 11 | 91 | 92 | 75 | 27 | 95 | 89 | 18 | 137 | - | - | - | - | - | - | - | - |
| 1800 | 4.0 | 16 | 95 | 107 | 78 | 27 | 104 | 89 | 18 | 137 | - | - | - | - | - | - | - | - |
| 1825 | 4.0 | 4 | 81 | 95 | 76 | 28 | 81 | 86 | 16 | 137 | - | - | - | - | - | - | - | - |
| 1850 | 4.0 | 11 | 81 | 88 | 76 | 27 | 97 | 89 | 16 | 137 | - | - | - | - | - | - | - | - |
| 1875 | 4.0 | 12 | 82 | 86 | 76 | 28 | 92 | 88 | 16 | 140 | -103 | 130 | -100 | 110 | -214 | 84 | -235 | 82 |
| 1900 | 4.0 | 13 | - | - | - | - | - | - | 17 | 140 | - | - | - | - | - | - | - | - |
| 1925 | 4.0 | 11 | - | - | - | - | - | - | 17 | 140 | - | - | - | - | - | - | - | - |
| 1950 | 4.0 | 12 | - | - | - | - | - | - | 17 | 140 | - | - | - | - | - | - | - | - |
| 1975 | 4.0 | 1 | 83 | 83 | 76 | 28 | 83 | 81 | - | 111 | - | 111 | - | 130 | -131 | 83 | -161 | 83 |
| TRANSVERSE SPECIMENS | | | | | | | | | | | | | | | | | | |
| 1750 | 4.0 | 11 | 135 | 166 | 50 | 15 | 83 | 85 | 42 | 31 | 74 | 29 | 47 | 29 | 47 | 29 | 47 | 27 |

TABLE 8

POLYMER LETTERS

[illegible]

* Longitudinal Impact Specimens.
 17 measured at 120 deg F by 4 hr.

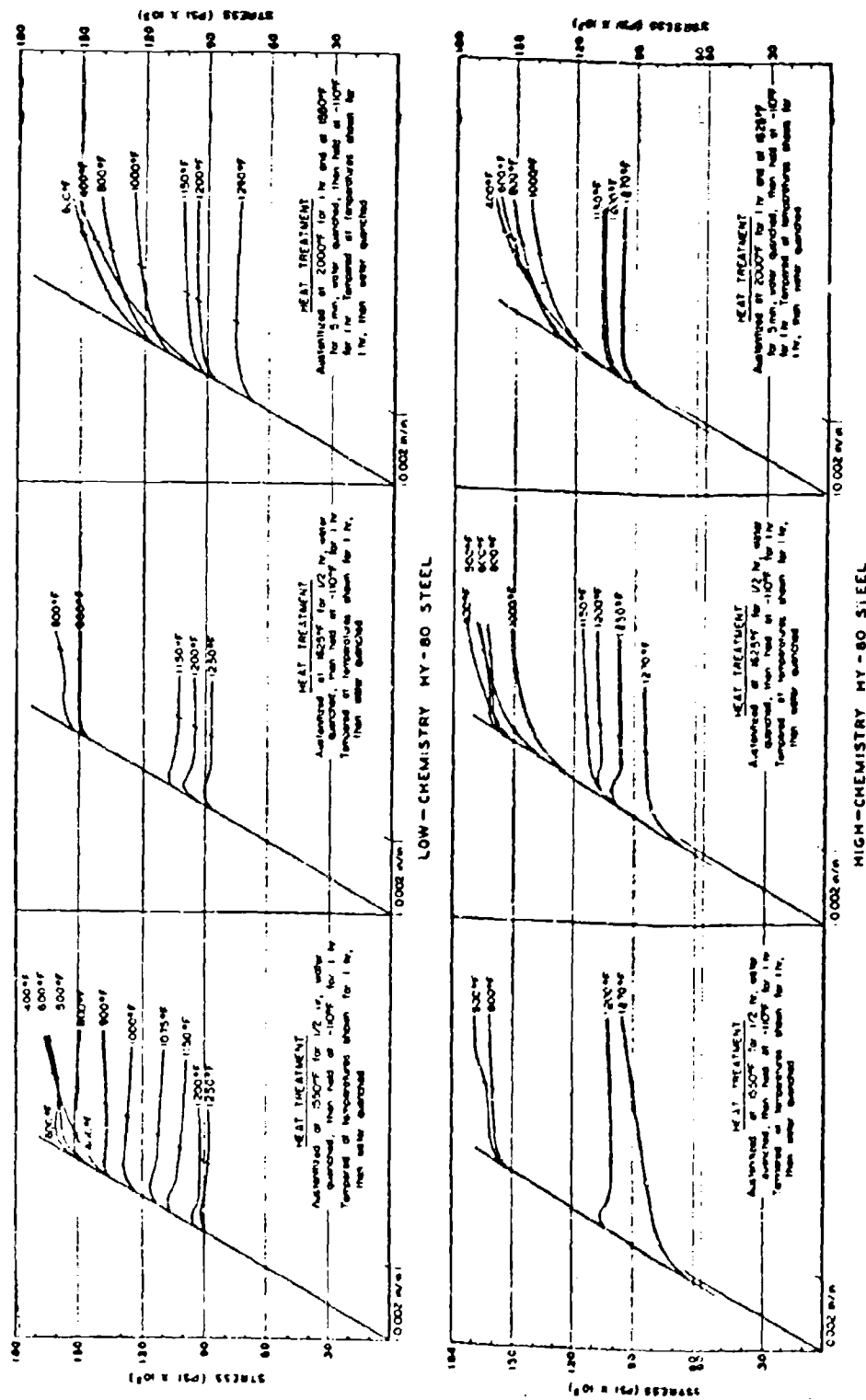


Figure 10 - Effects of Various Tempering Temperatures on Yielding Characteristics of Low- and High-Chemistry HY-80 Steel after Quenching from Various Austenitizing Treatments

There appears to be a combined effect of austenitizing temperature and 1270° F tempering temperature on the yielding characteristics of high-chemistry HY-80 steel. It is shown in Figure 10 that the yielding characteristics resulting from the 1270° F temper for both the 1550 and 1625° F austenitizing treatments change from discontinuous to curvilinear; the curve obtained from the specimen austenitized at 1550° F is more curvilinear than that for the specimens austenitized at 1625° F. The specimens tempered at 1270° F after being quenched from the duplex austenitizing temperatures of 2000 to 1625° F show a plateau type of yielding. The effects of austenitizing are very noticeable for this tempering temperature when the proportional limit data compiled in Table 6 are compared. For the austenitizing temperatures of 1550 and 1625° F, the resulting proportional limits are at the 60,000-psi level, whereas the limits for the specimens which were tempered at 1270° F and had the duplex austenitizing treatment, 2000 to 1625° F, are approximately 20,000 psi higher.

Notch Brittleness

In general, the notch-brittleness properties of both the low- and high-chemistry HY-80 steels showed an increase in transition temperature with increasing austenitizing temperatures and with decreasing tempering temperatures.

In comparing the Charpy V-notch data for the low- and high-chemistry steels for a given tempering temperature, the higher mechanical properties of the high-chemistry HY-80 steel must be considered or an erroneous conclusion may be drawn as to the effects of chemistry. Although the majority of the Charpy V-notch tests for both the low- and high-chemistry HY-80 steels were taken from the transverse direction of plate roll, the results from the few longitudinal specimens indicate higher energies and lower transition temperatures. Mechanical property strength, Charpy V-notch data, and the relationships between longitudinal and transverse impact data for both the low- and high-chemistry steels will be fully discussed in a subsequent section of this report. However, it should be noted from Tables 5 and 6 that, for a given strength level, the Charpy V-notch energy levels are the same for a given fibrous condition while the fibrous transition temperatures are dependent upon the austenitizing treatment, tempering treatment, and chemistry.

Tables 5 and 6 and Figures 11 through 16 clearly show the effects of tempering temperatures on the energy-absorption level and fibrous transition temperatures for a given austenitizing treatment. The curves of Charpy V-notch energy absorbed versus temperature for specimens tempered below 600° F are very similar; see especially Figures 11 and 15.

From these data and figures there appears to be an increase in Charpy V-notch energy-absorption level and a decrease in fibrous transition temperature for tempering temperatures between 300 and 1150° F. For tempering temperatures above 1150° F the transverse data show a juxtaposition in lateral expansion, percent fibrous fracture, and energy absorption for any austenitizing treatment.

(Text continued on page 30.)

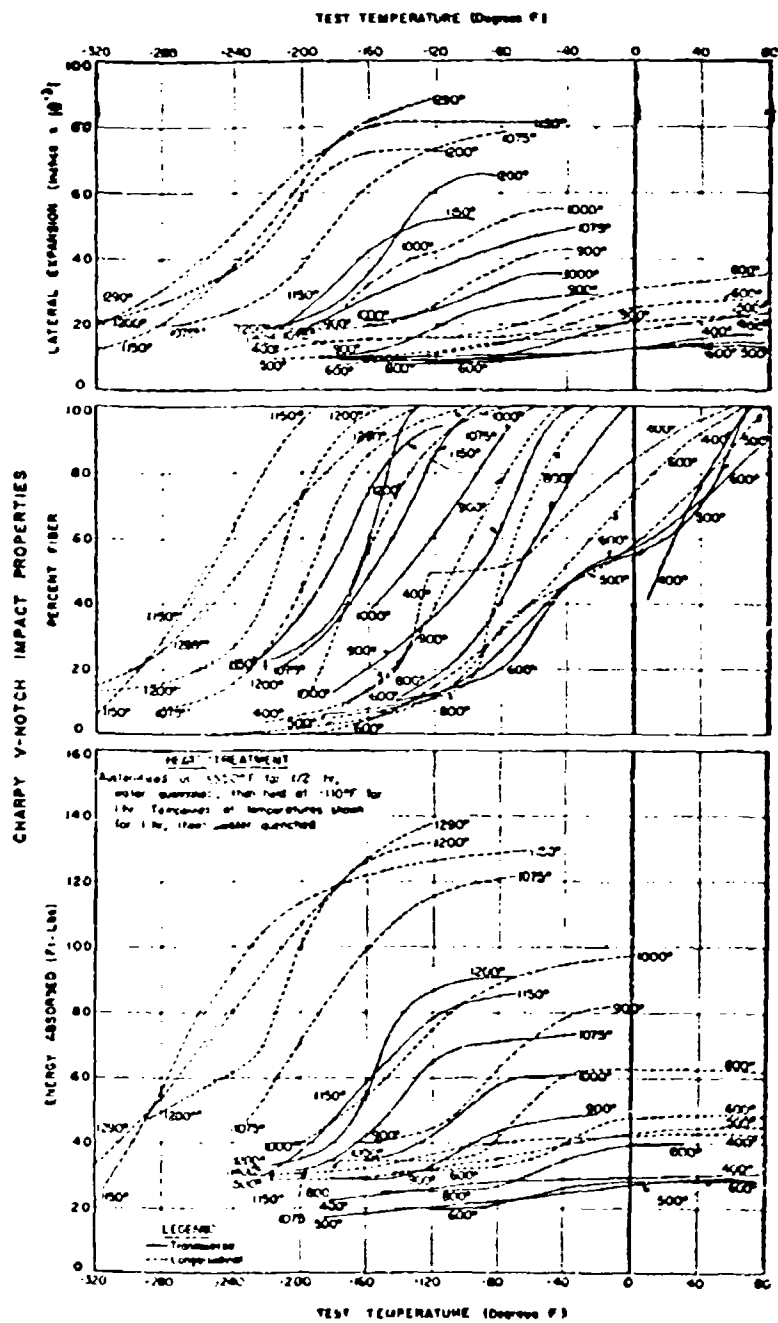


Figure 11 -- Effects of Tempering Temperature on Charpy V-Notch Impact Properties of Low-Chemistry HY-80 Steel after Austenitizing at 1550° F

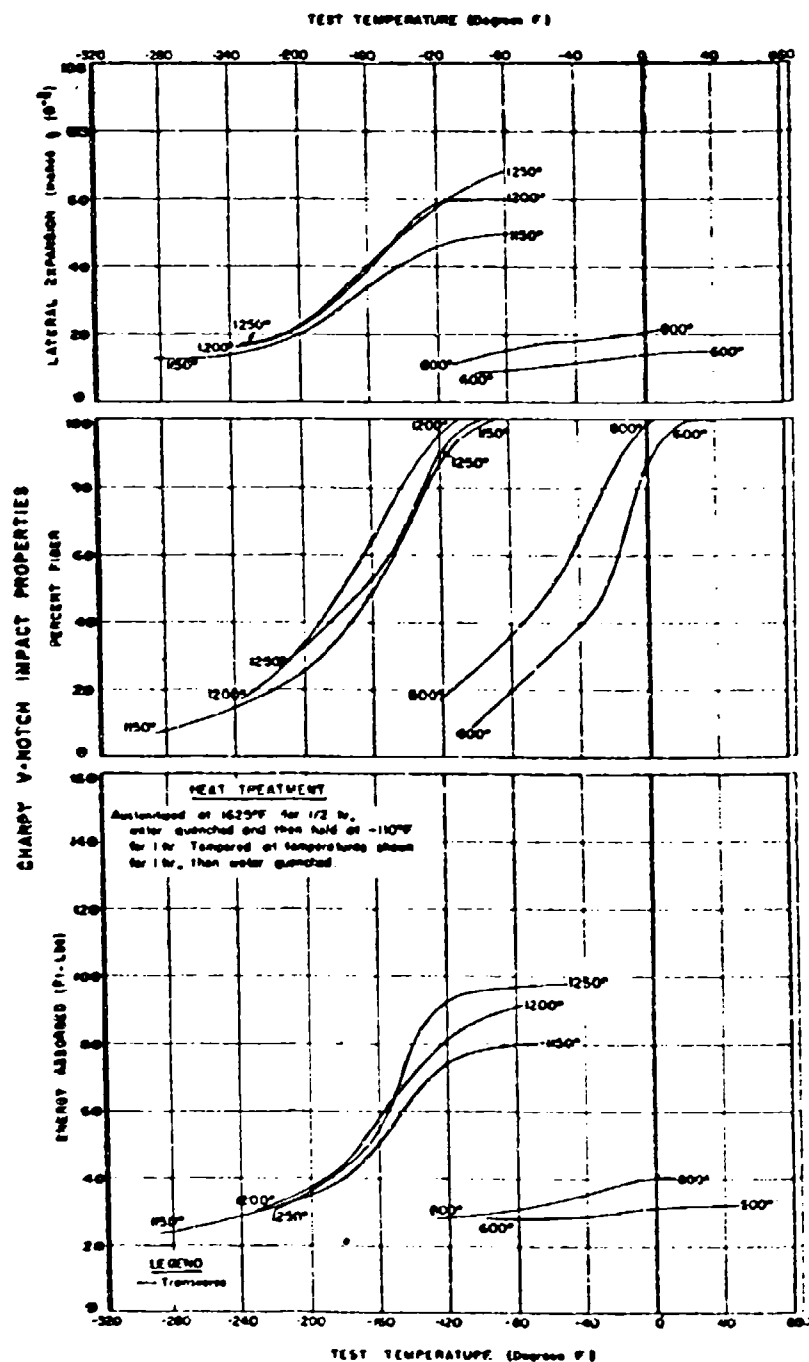


Figure 12 - Effects of Tempering Temperature on Charpy V-Notch Impact Properties of Low-Chemistry HY-80 Steel after Austenitizing at 1625° F

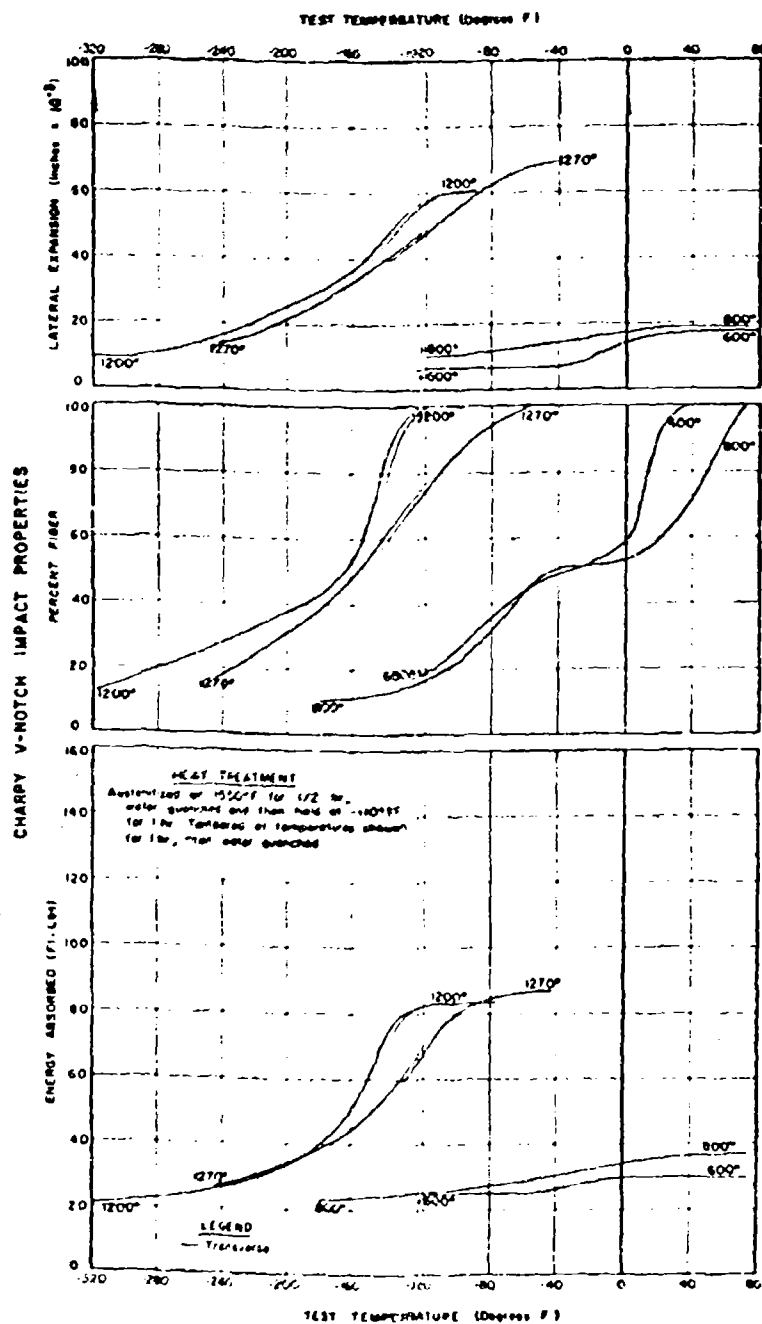


Figure 14 - Effects of Tempering Temperature on Transverse Charpy V-Notch Impact Properties of High-Chemistry HY-80 Steel after Austenitizing at 1550°F

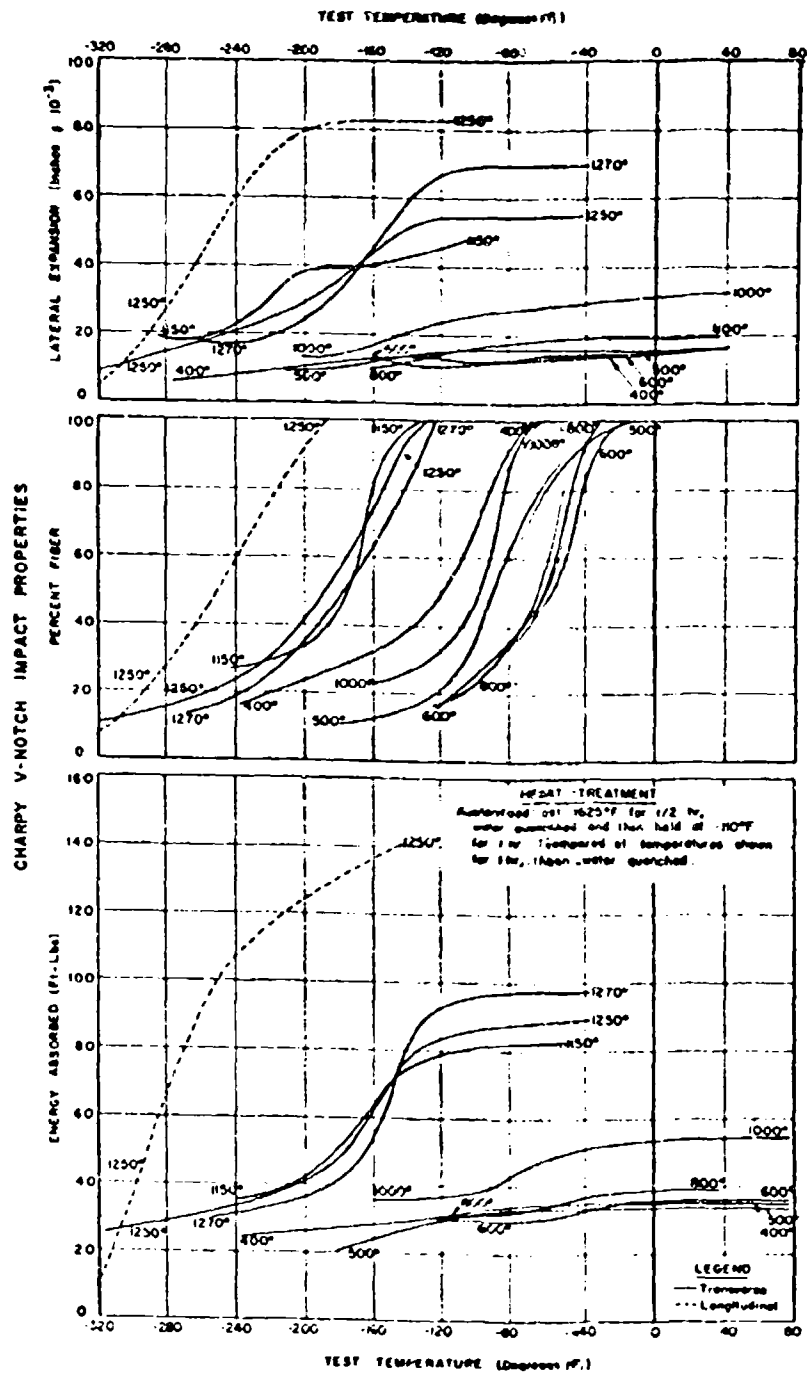


Figure 15 - Effects of Tempering Temperature on Charpy V-Notch Impact Properties of High-Chemistry HY-80 Steel after Austenitizing at 1625° F

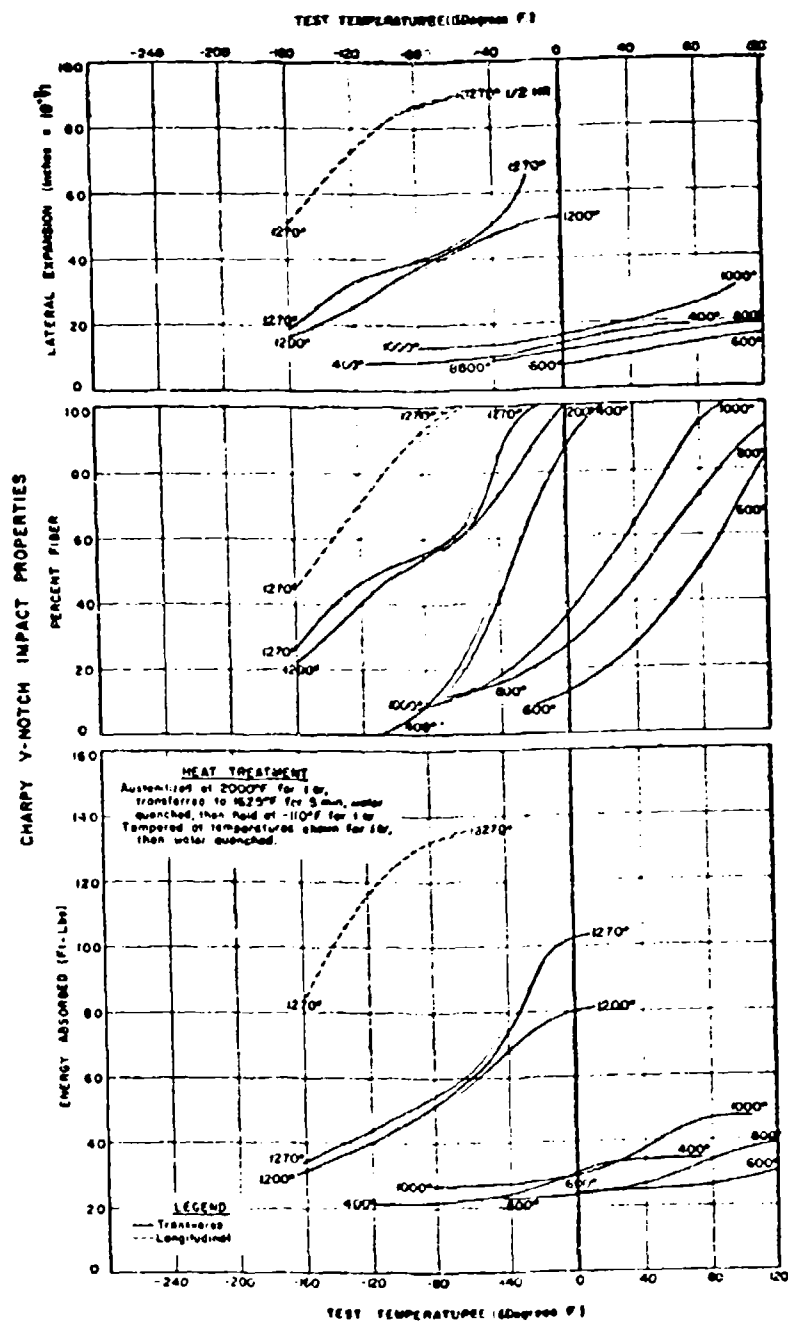


Figure 16 – Effects of Tempering Temperature on Charpy V-Notch Impact Properties of High-Chemistry HY-80 Steel after Austenitizing at 2000° F

Microstructure

The effects of tempering temperature on the martensitic microstructure for both low and high austenitizing temperatures are depicted for low-chemistry HY-80 steel in Figure 17 and for high-chemistry HY-80 in Figure 18.

The microstructures, as expected, for both the low- and high-chemistry steels show progressive spheroidization of carbides from the as-quenched martensitic state to the highly tempered martensitic structures. No precipitated products were discernible for the low tempering temperatures, 500 to 600° F, nor for the structures tempered at 1150 to 1200° F. Metallographic examination of specimens tempered at 1270° F revealed a still greater spheroidization of carbides.

EFFECTS OF VARIOUS TEMPERING TIMES AT VARIOUS TEMPERING TEMPERATURES

Tempering times at a given temperature were investigated to study their effects on the tensile and notch-brittleness properties of HY-80 steels.

Tensile Properties

A study of the tensile properties compiled in Table 7 indicates that the yield and tensile properties decrease with increasing times at tempering temperatures. To meet yield-strength specification requirements it takes the low-chemistry HY-80 steel quenched to a fully martensitic structure 2 to 3 hr at the 1150° F tempering temperature whereas the high-chemistry HY-80 steel does not meet the maximum yield-strength requirements after 3 hr at 1150° F. If these data are projected, it will take approximately 6 hr at 1150° F for the high-chemistry HY-80 steel to meet the specified yield strength.

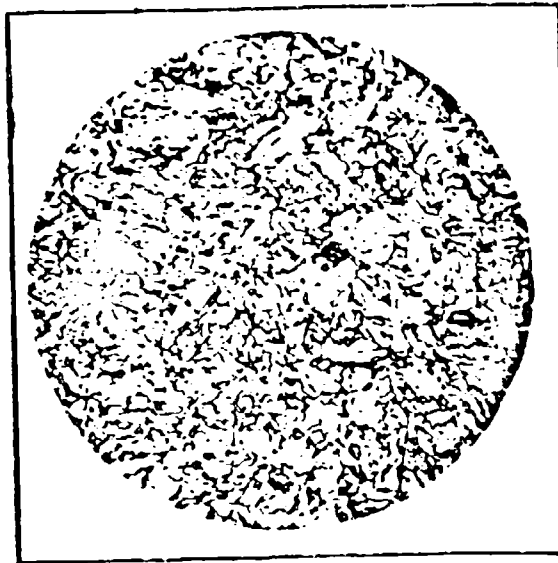
Notch Brittleness

The effects of tempering time for various tempering temperatures on the Charpy V-notch transition temperatures are shown in Figures 19, 20, and 21. The effects of tempering time were investigated more completely for the low-chemistry HY-80 steel than for the high-chemistry HY-80 steel because of the insufficient quantity of the high-chemistry material.

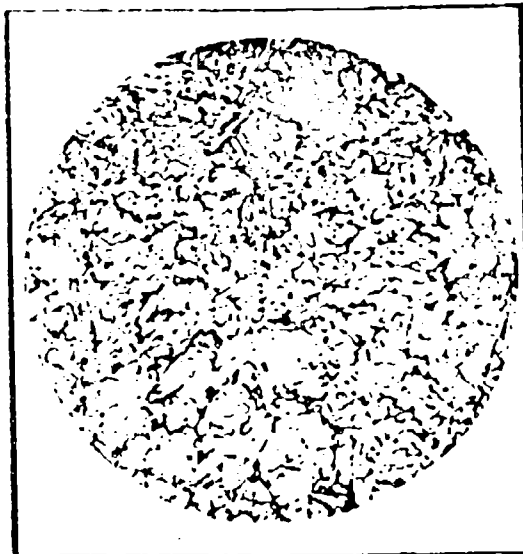
Charpy V-notch transition temperatures of the low-chemistry HY-80 steel for tempering temperatures below 1000° F were investigated for times up to and including 8 hr at temperature. Tempering temperatures above 1150° F were investigated up to and including 16 hr. The results are only indicative for the holding times investigated.

The Charpy V-notch transition temperature for the low-chemistry steel, Figure 19, appears not to be affected by the tempering holding times investigated. Figure 20 compares the effects of tempering at 1200° F for holding times of 1 to 16 hr for two austenitizing temperatures, 1550 and 1625° F. The results for these tempering temperatures and holding times

(Text continued on page 37.)



1150° F

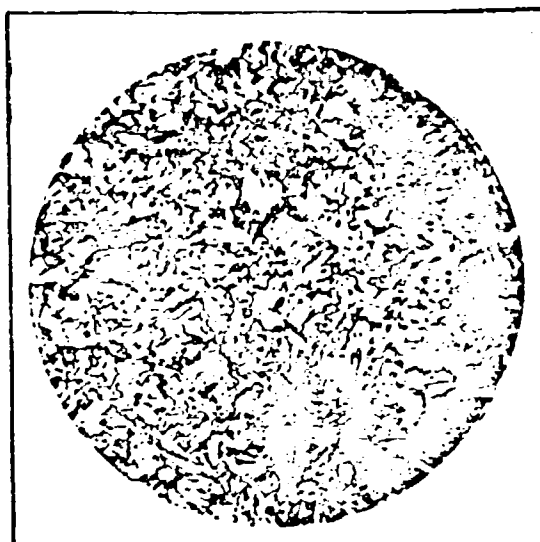


1000° F

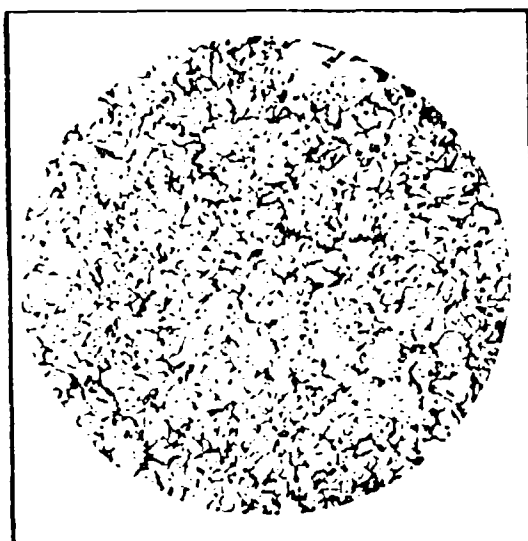


600° F

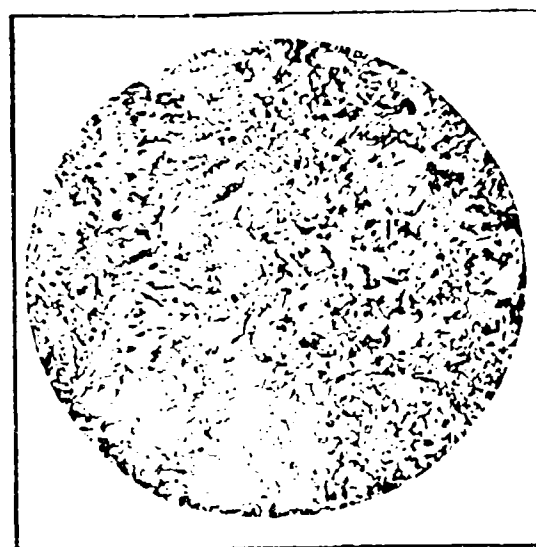
Figure 17 - Photomicrographs at 750 X of Low-Chemistry HY-60 Steel Tempered at Various Temperatures after Quenching from 1550° F



1150° F



1000° F



600° F

Figure 18 - Photomicrographs at 750 X of High-Chemistry HY-80 Steel Tempered at Various Temperatures after Quenching from 14625° F

TABLE 7 - Effects of Various Tempering Times at Various Temperatures on the Mechanical Properties of Low- and High-Chemistry HY-80 Steel after Quenching from Various Austenitizing Treatments

| Austenitizing Temperature (deg F) | Tempering Time (hours) | Yield Strength ksi | Ultimate Tensile Strength ksi | Percent Reduction in Area | Percent Elongation in 1 inch | Ratio $\frac{P.L.}{Y.S.} \times 100$ | Midspan Recess 'C' Scale | Batch Brittleness | | | | | | | | |
|---|------------------------------|--------------------------|--|---------------------------------|------------------------------------|---|--------------------------------|-----------------------|--------|----------------------|--------|----------------------|--------|----------------------|--------|--|
| | | | | | | | | 100% Fibrous Fracture | | 80% Fibrous Fracture | | 50% Fibrous Fracture | | 30% Fibrous Fracture | | |
| Gas F | | | | | | | | Temp | Energy | Temp | Energy | Temp | Energy | Temp | Energy | |
| (% hour) | | | | | | | | deg F | ft-lb | deg F | ft-lb | deg F | ft-lb | deg F | ft-lb | |
| Longitudinal Specimens of Low-Chemistry HY-80 Steel | | | | | | | | | | | | | | | | |
| 1550 | 1 | 99 | 120 | 111 | 75 | 97 | 24 | 123 | -115 | 117 | -210 | 104 | -214 | 80 | - | |
| 1550 | 16 | 87 | 88 | 100 | 75 | 98 | 21 | - | - | - | - | - | - | - | - | |
| Transverse Specimens of Low-Chemistry HY-80 Steel | | | | | | | | | | | | | | | | |
| 1550 | 1 | 146 | 148 | 155 | 17 | 35 | 36 | 40 | 31 | 35 | 37 | 21 | 33 | 37 | 21 | |
| 1550 | 3 | - | - | - | - | - | 37 | 42 | 31 | 35 | 37 | 21 | 33 | 37 | 21 | |
| 1550 | 8 | - | - | - | - | - | 36 | 43 | 30 | 36 | 30 | 36 | 30 | 36 | 30 | |
| 1550 | 16 | 131 | 140 | 149 | 17 | 35 | 35 | 43 | 28 | 43 | 43 | 43 | 43 | 43 | 43 | |
| 1550 | 1 | - | - | - | - | - | 34 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | - | - | - | - | - | 35 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | - | - | - | - | - | 35 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 122 | 132 | 142 | 17 | 35 | 35 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | - | - | - | - | - | 31 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | - | - | - | - | - | 31 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | - | - | - | - | - | 30 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 100 | 120 | 130 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 106 | 123 | 135 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 104 | 124 | 134 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 93 | 114 | 124 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 81 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 3 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 8 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 16 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550 | 1 | 84 | 104 | 114 | 17 | 35 | 33 | 44 | 31 | 31 | 31 | 31 | 31 | 31 | 31 | |
| 1550</ | | | | | | | | | | | | | | | | |

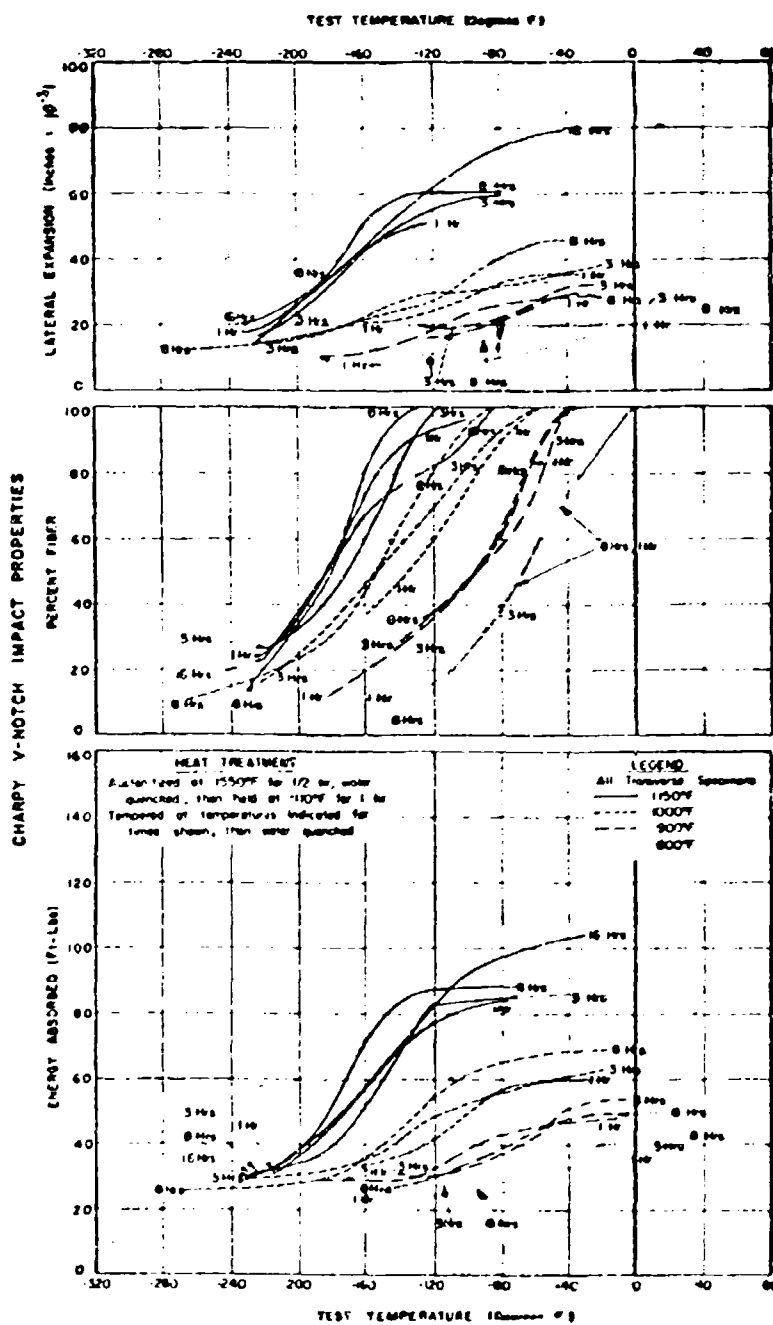


Figure 19 - Effects of Various Tempering Times and Various Tempering Temperatures on Transverse Charpy V-Notch Impact Properties of Low-Chemistry HY-80 Steel Austenitized at 1550° F

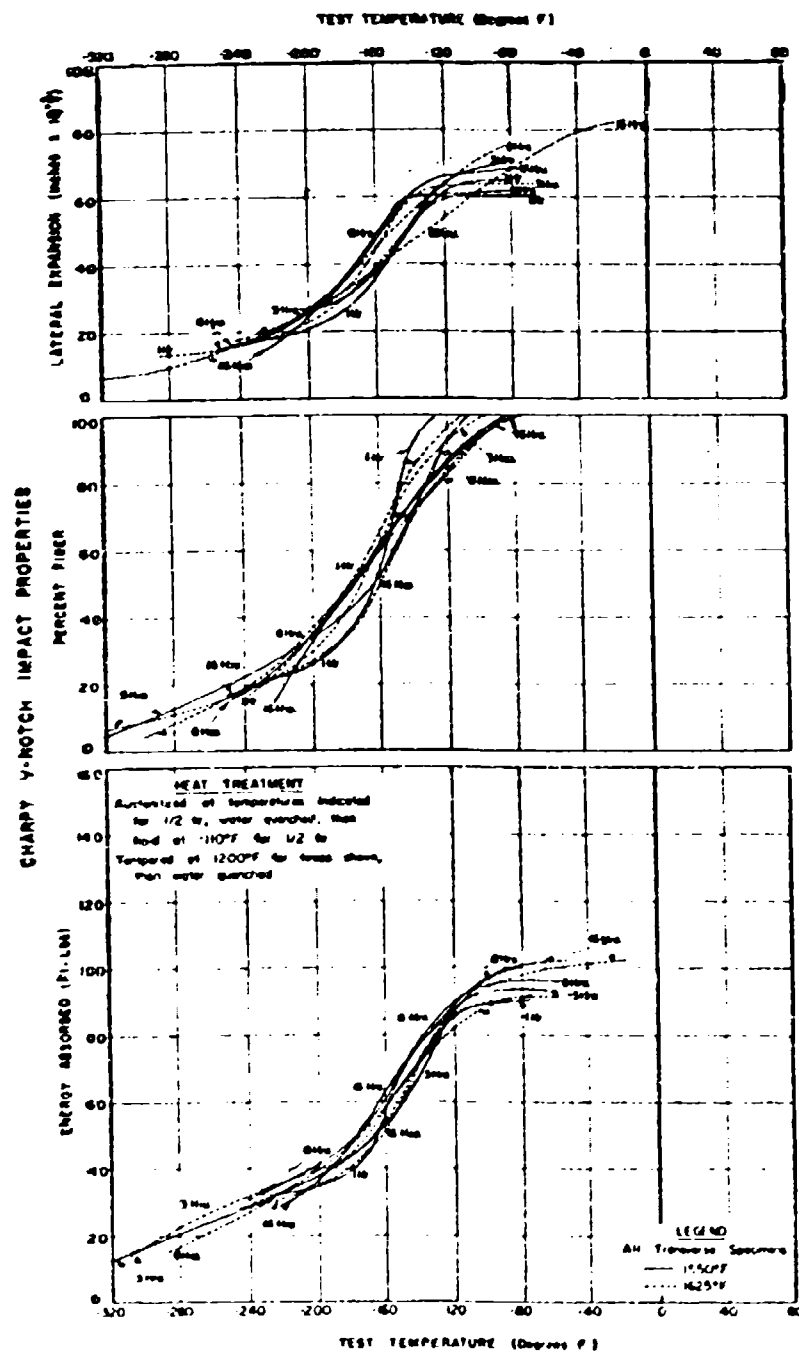


Figure 20 - Effects of Various Tempering Times at 1200° F on Transverse Charpy V-Notch Impact Properties of Low-Chemistry HY-60 Steel

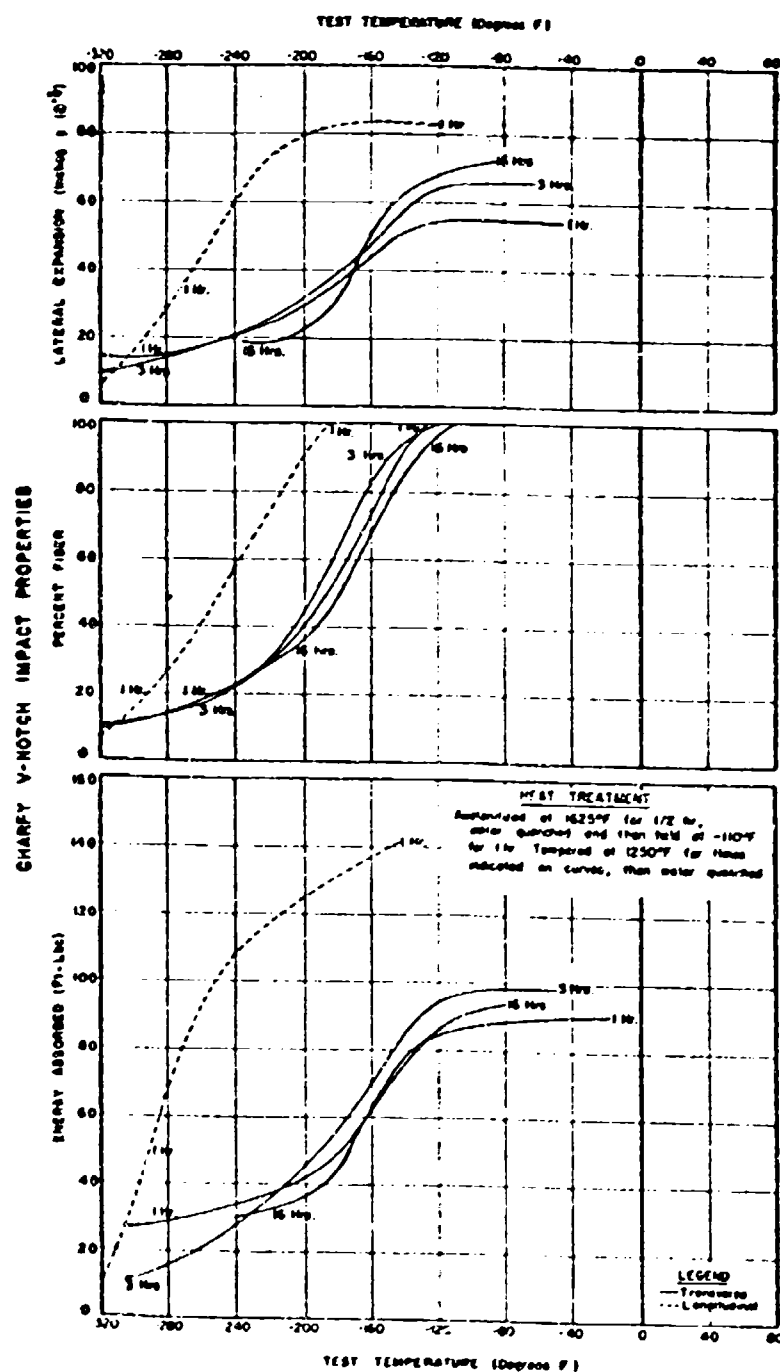


Figure 21 - Effects of Various Tempering Times at 1250° F on Charpy V-Notch Impact Properties of High-Chemistry HY-80 Steel

indicate that normal austenitizing temperatures have no effect on notch brittleness for the times investigated. Superimposing Figure 20 on Figure 19, it can be seen that the 1200° F tempers fall on the transition curves obtained by tempering at 1150° F.

For the high-chemistry HY-80 steel, the effects of holding time at one tempering temperature, 1250° F, were investigated; see Figure 21. The Charpy V-notch transition temperatures for this one tempering temperature indicate that a fully martensitic high-chemistry HY-80 steel is not detrimentally affected by holding times up to and including 16 hr.

Microstructure

Ethereal picric acid with Zephiran Chloride etch revealed no embrittlement of the microstructure for any given tempering temperatures with the holding times investigated.

CORRELATION AND INTERRELATION OF DATA

These data will be correlated to establish base lines for future evaluations of the effects of other variables on mechanical and notch-brittleness properties. Maximum energy and fibrous appearance (100-, 80-, 50-, and 30-percent fiber) of the Charpy V-notch specimens were selected as constants for relating tensile properties to other Charpy V-notch impact results. In addition, correlations between properties are presented such as longitudinal to transverse Charpy V-notch properties, longitudinal tensile properties to Charpy V-notch fibrous transition temperatures, and, finally, hardness to yield and tensile strengths. To consider properly the large number of variables involved, each problem was statistically programmed for the IBM 709 computer. Figures 22 through 24 and 26 are the results of derived least-square equations. The equations for the least-square fit and its sigma (σ) values given for each developed curve are the best for the obtained data. For three curves a fourth-degree equation was obtained which had a sigma value which was smaller in the second decimal place. A sample plot was made using the third- and fourth-degree equations, and it was observed that the third-degree equation was as adequate as the more cumbersome fourth-degree equation. The sigma values obtained from third- and fourth-degree equations were always the same; therefore, only third-degree equations were used in plotting the curves, except in one case a second-degree curve was used. The limits of the independent variable were the minimum and maximum test data obtained except in Figure 23 where the maximum limit was set for data obtained below tempers of 600° F.

The Appendix is a compilation of the least-square equations and their sigma values for curves shown in Figures 22 through 24 and 26 through 28.

CORRELATION BETWEEN LONGITUDINAL TENSILE AND CHARPY V-NOTCH PROPERTIES

Figures 22 and 23 show the least-square fit relating longitudinal yield and tensile strengths to transverse Charpy V-notch properties (energy absorption and fibrous transition temperatures) for a given Charpy V-notch fibrous condition. The least-square equations

(Text continued on page 41.)

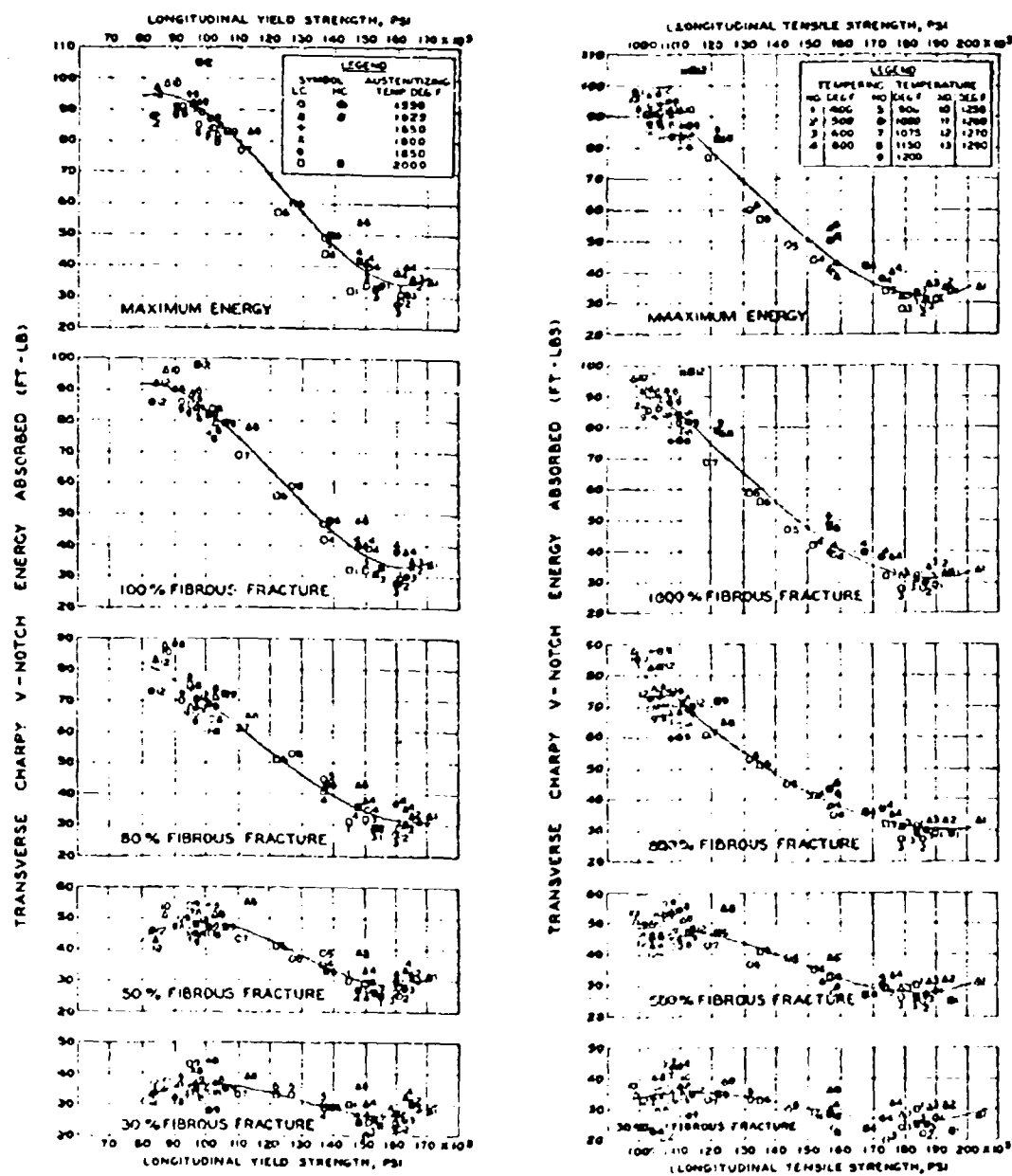


Figure 22 - Correlation between Longitudinal Strength and Transverse Charpy V-Notch Energy Absorbed at Maximum Energy and at a Given Fibrous Fracture Appearance for Fully Quenched and Tempered HY-80 Steel

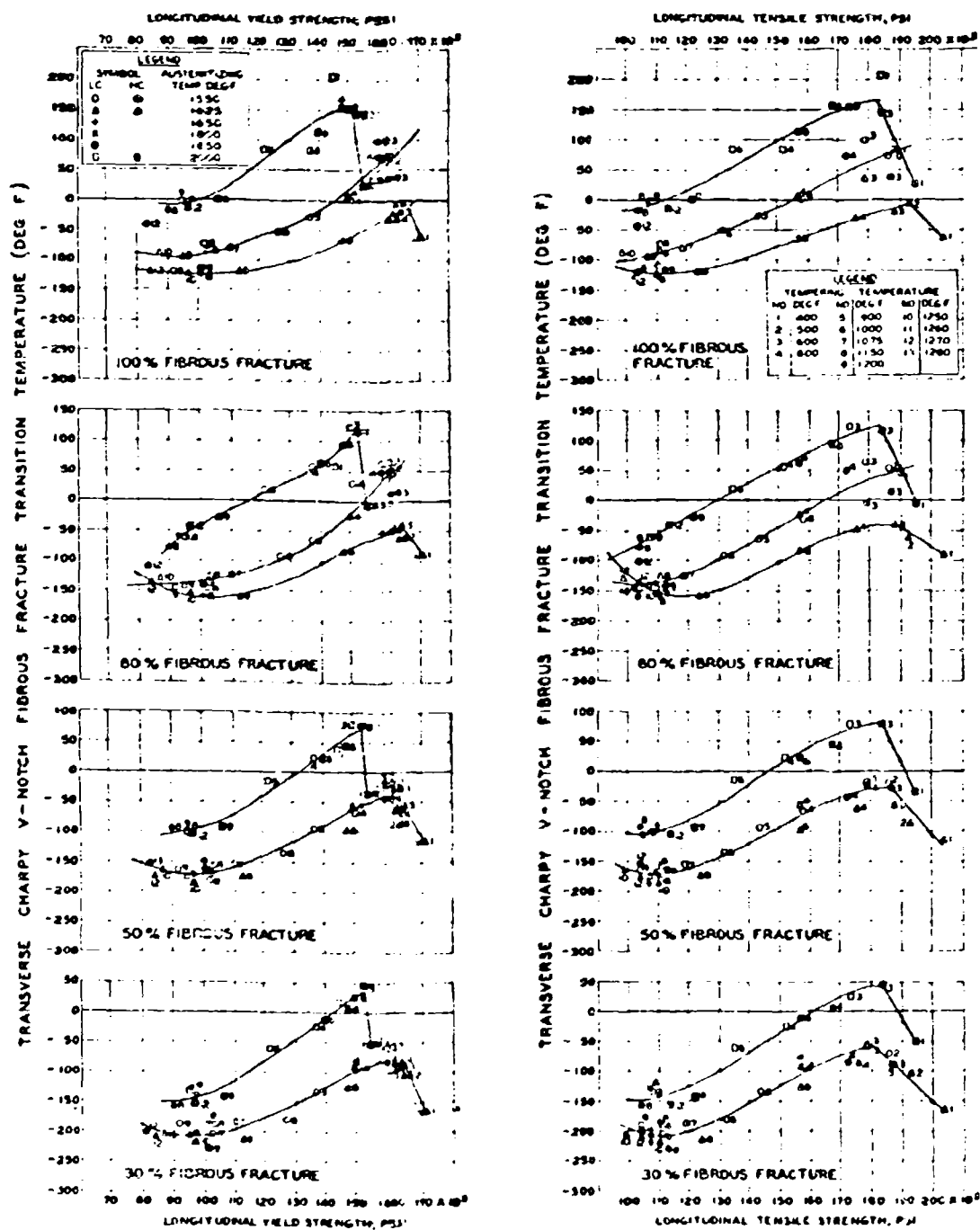


Figure 23 - Correlation between Longitudinal Strength and Transverse Charpy V-Notch Fibrous Fracture Transition Temperatures for Fully Quenched and Tempered HY-60 Steel

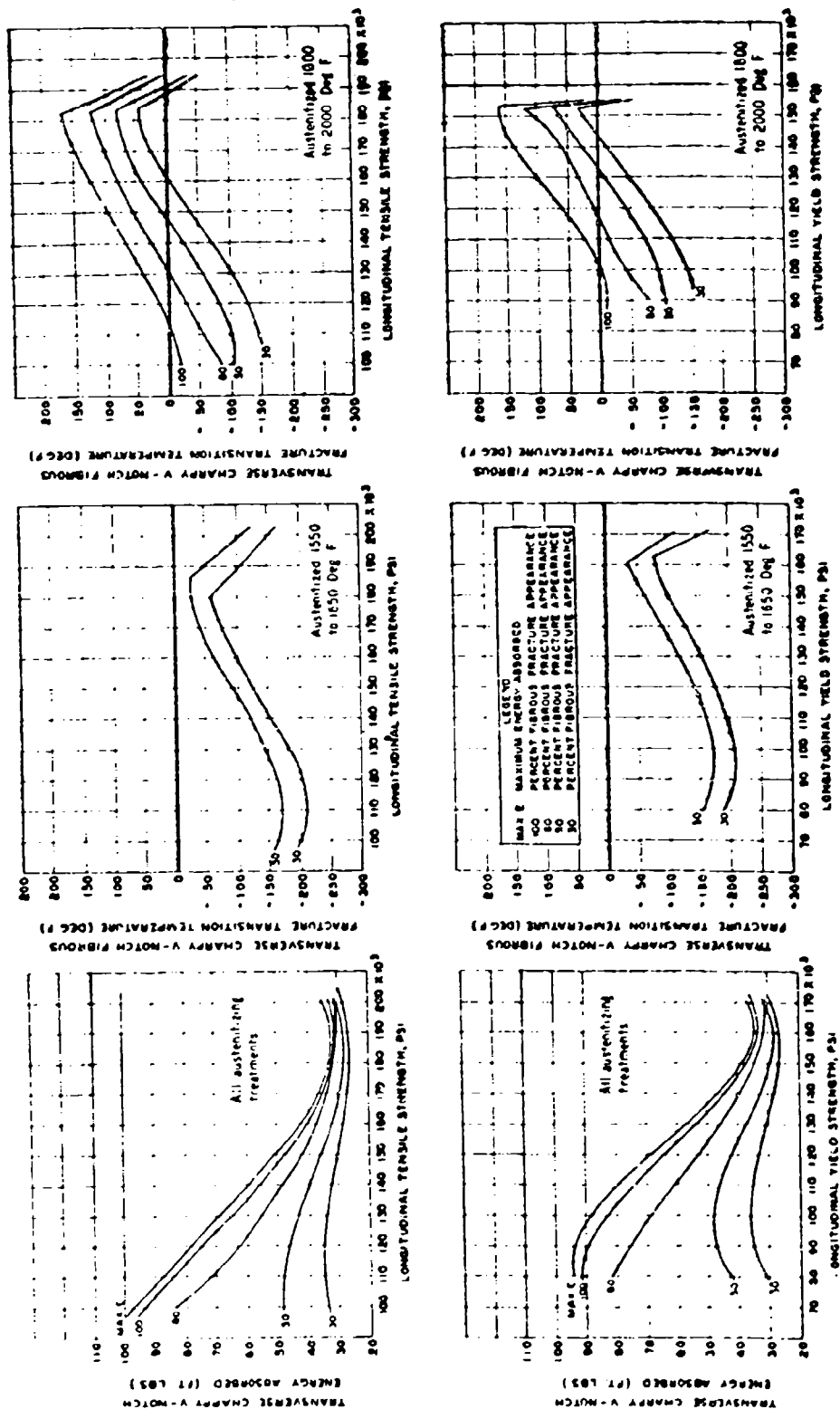


Figure 24 - Compilation of Least-Square Curves Relating Transverse Charpy V-Notch Energy Absorption and Fibrous Fracture Transition Temperature at a Given Yield Strength for Both High and Low Austenitizing Temperatures

given in the Appendix for developing Figure 22 were derived from both the low- and high-chemistry test data. Equations derived for each individual chemistry showed that its sigma value was slightly lower than the sigma value of the combined chemistries. For example, the curve relating the maximum Charpy V-notch energy absorbed to yield strength for both chemistries has a sigma value of 5.03; the sigma values for the low- and the high-chemistries are, respectively, 3.05 and 4.99. It can be considered that the sigma-value deviations for the combined chemistries given in the Appendix for Figure 22 fall well within experimental error.

Figure 23 shows that for the high austenitizing temperatures, 1800 to 2000° F, the results fall on one curve for any given Charpy V-notch fibrous fracture condition. For the low austenitizing temperatures, 1550 to 1650° F, the data obtained from the 100- and 80-percent Charpy V-notch fibrous fractures fall on two distinct curves. The low-chemistry HY-80 austenitized between 1550 and 1650° F and the high-chemistry HY-80 austenitized at 1625° F fall on the intermediate curve; whereas, the high-chemistry HY-80 austenitized between 1625 and 1650° F fall on the lower curve. This data indicates that the austenitizing temperature and also the chemistry have a direct effect on the Charpy V-notch fibrous transition temperature for the 100- and 80-percent fibrous fracture conditions. However, for the 50- and 30-percent fibrous fracture conditions, the fibrous transition temperatures results for either chemistry are dependant only on the range in which the specimens were austenitized, that is, the specimens austenitized between 1550 and 1650° F fall on one curve, while those austenitized between 1800 and 2000° F fall on the higher curve.

Figure 24 is a compilation of the least-square curves of Figures 22 and 23; however, the 100- and 80-percent fibrous-transition-temperature curves for the 1550 to 1650° F austenitizing temperatures are omitted from this compilation because of the large effect of chemistry as depicted in Figure 23. For the steels investigated the transverse Charpy V-notch energy absorption for a given fibrous condition can be predicted for any desired strength level from Figure 24; however, only a semiquantitative prediction can be obtained for the fibrous-fracture transition temperatures.

The effects of directionality Charpy V-notch properties for low-chemistry HY-80 steel austenitized at 1550° F are shown in Figure 25. It is interesting to note that, for a given fibrous fracture appearance and for strength levels between 110,000 and 160,000 psi, the specimens for longitudinal and transverse Charpy V-notch fibrous transition temperatures appear to merge together, whereas there is a distinct spread between the curves for energy-absorption levels.

CORRELATIONS BETWEEN LONGITUDINAL AND TRANSVERSE CHARPY V-NOTCH DATA AT MAXIMUM ENERGY OR AT A GIVEN PERCENT FIBER

In the preceding section in which data relating to the effects of varying austenitizing and tempering temperatures on HY-80 steels were presented, it was noted that there may be a correlation between the Charpy V-notch energy-absorption levels of longitudinal and transverse data for maximum energy absorbed and for a given Charpy V-notch fibrous fracture appearance.

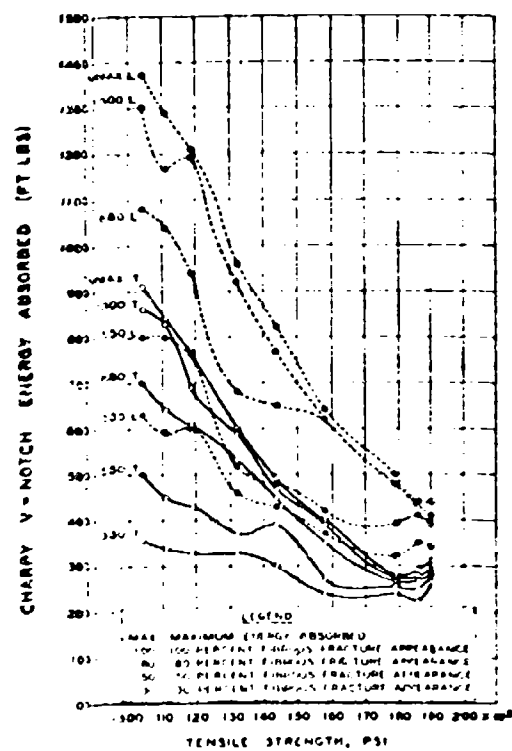
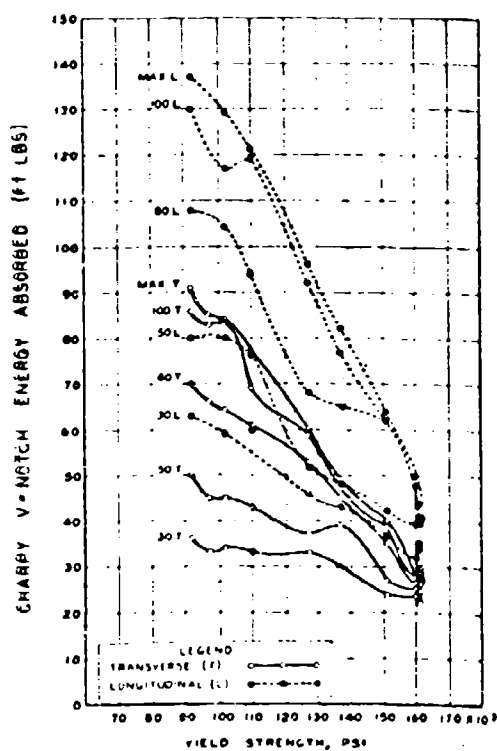
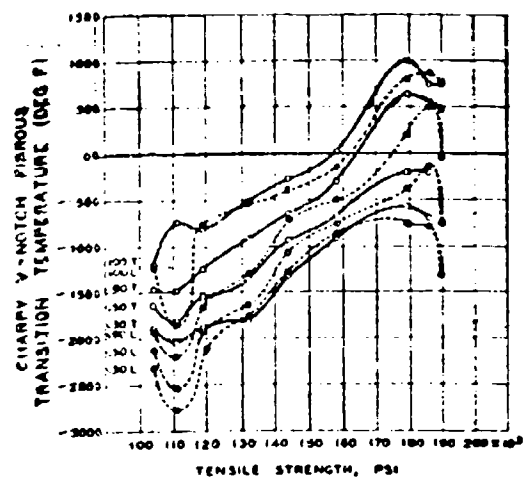
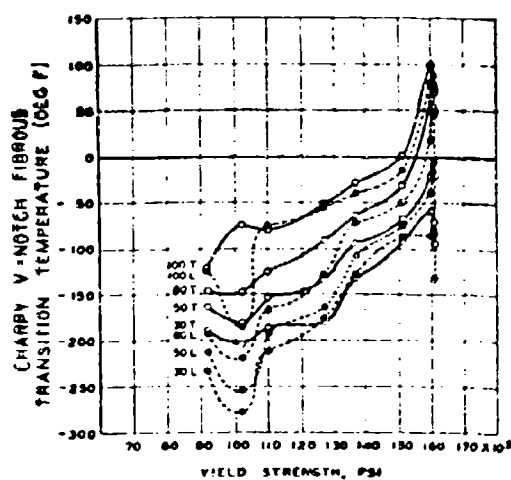


Figure 25 - Comparison of Effects of Direction on Charpy V-Notch Impact Properties (Energy Absorbed and Transition Temperature) at a Given Strength Level and for a Given Percent Fibrous Fracture Appearance for Low-Chemistry HY-80 Steel Austenitized at 1550° F

Figure 26 depicts, for a given Charpy V-notch fibrous fracture appearance, the correlation between longitudinal and transverse fibrous transition temperatures and the correlation between longitudinal and transverse energy-absorption levels for the steels used in this investigation.

The correlations given in Figure 26 are to be considered as indicative, since the curves are fitted to a limited number of test points. With additional data it would be expected that the degree of fit will not change but that there will be a slight shift in the curve itself. The sigma value of 7 ft-lb, given in the Appendix, for the transverse energy versus the longitudinal energy is within experimental error, whereas the sigma value of 25° F for the fibrous transition temperatures is considered large.

CORRELATION BETWEEN HARDNESS AND TENSILE PROPERTIES

Figure 27 depicts the relation between yield and tensile strength and Rockwell C hardness for specimens austenitized between 1550 and 1650° F. Since Brinell hardness is usually related to tensile strength, this relationship is also shown in Figure 27. As previously discussed, specimens austenitized at 1800° F and above had lower hardnesses than those austenitized at lower temperature for corresponding strength levels. From the Appendix it can be seen that the least-square curves fitted to the high austenitizing temperature, Figure 28, have larger sigma values. Figure 28 shows the combined effects of chemistries and high-austenitizing treatment on the hardness for a given strength level.

DISCUSSION

The test results which have been presented show the effects of particular variables such as austenitizing temperatures and tempering temperatures on the mechanical properties of fully quenched, martensitic, production-produced, IY-80 steel plates of both low and high chemistry.

To understand the effects of varying heat-treatment on the properties of IY-80 steel, Charpy V-notch fibrous fracture appearance was selected as the criterion since it is believed that this property is more sensitive to change in microstructure than any other criterion.

In general, this investigation shows that IY-80 steels austenitized at any temperature and then quenched to a fully martensitic structure and tempered in accordance with the specification would meet the mechanical properties and Charpy V-notch impact requirements of Reference 3. For the latter property where high austenitizing temperatures are concerned, it is cautioned that the energy absorption cannot be considered as a true index for notch brittleness since the specification's longitudinal impact requirements, 50 ft-lb at -120° F for plates up to 61.2 lb per sq ft and 30 ft-lb at -120° F for heavier plates were established empirically.²⁰

(Text continued on page 47.)

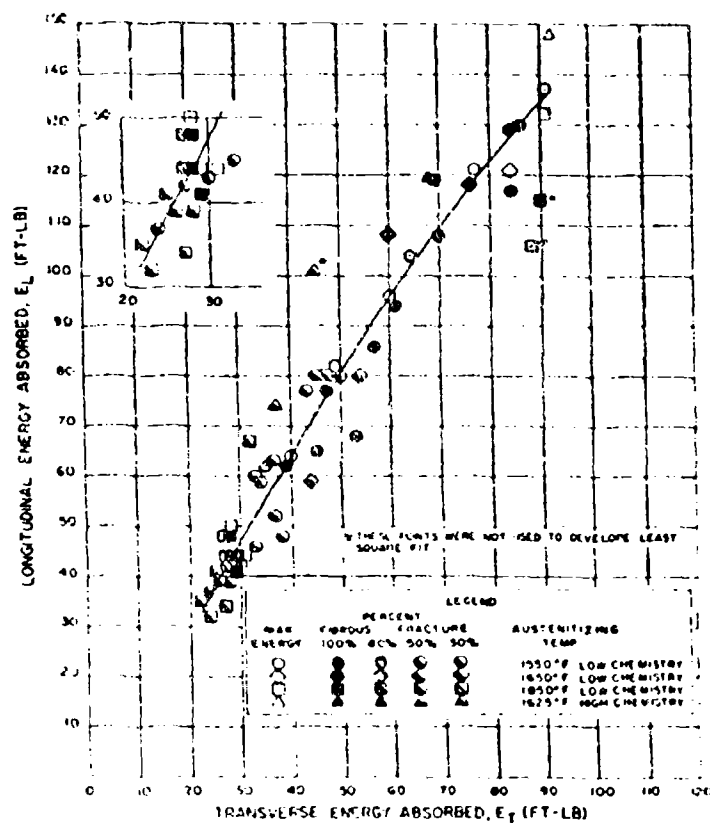
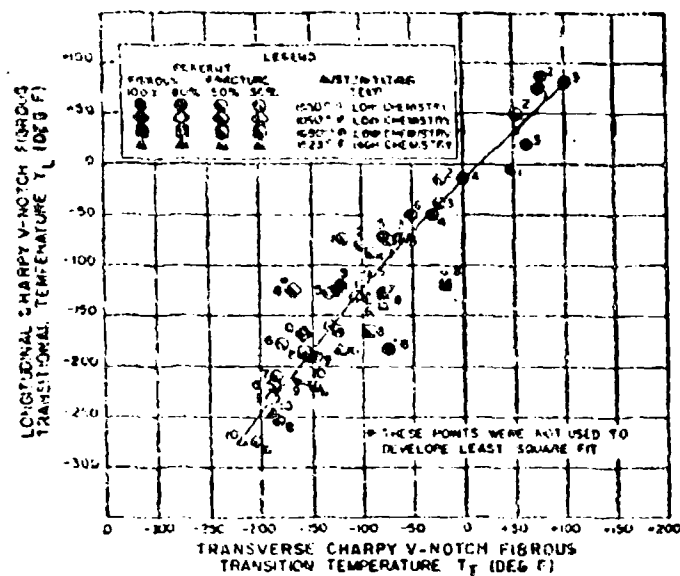


Figure 26 - Correlation of Transverse and Longitudinal Charpy V-Notch Impact Properties (Energy Absorbed and Fibrous Fracture Transition Temperature) for Maximum Energy and for any Given Percent Fibrous Fracture Appearance of a Fully Quenched, Straight-Away-Rolled Low-Chemistry HY-80 Steel

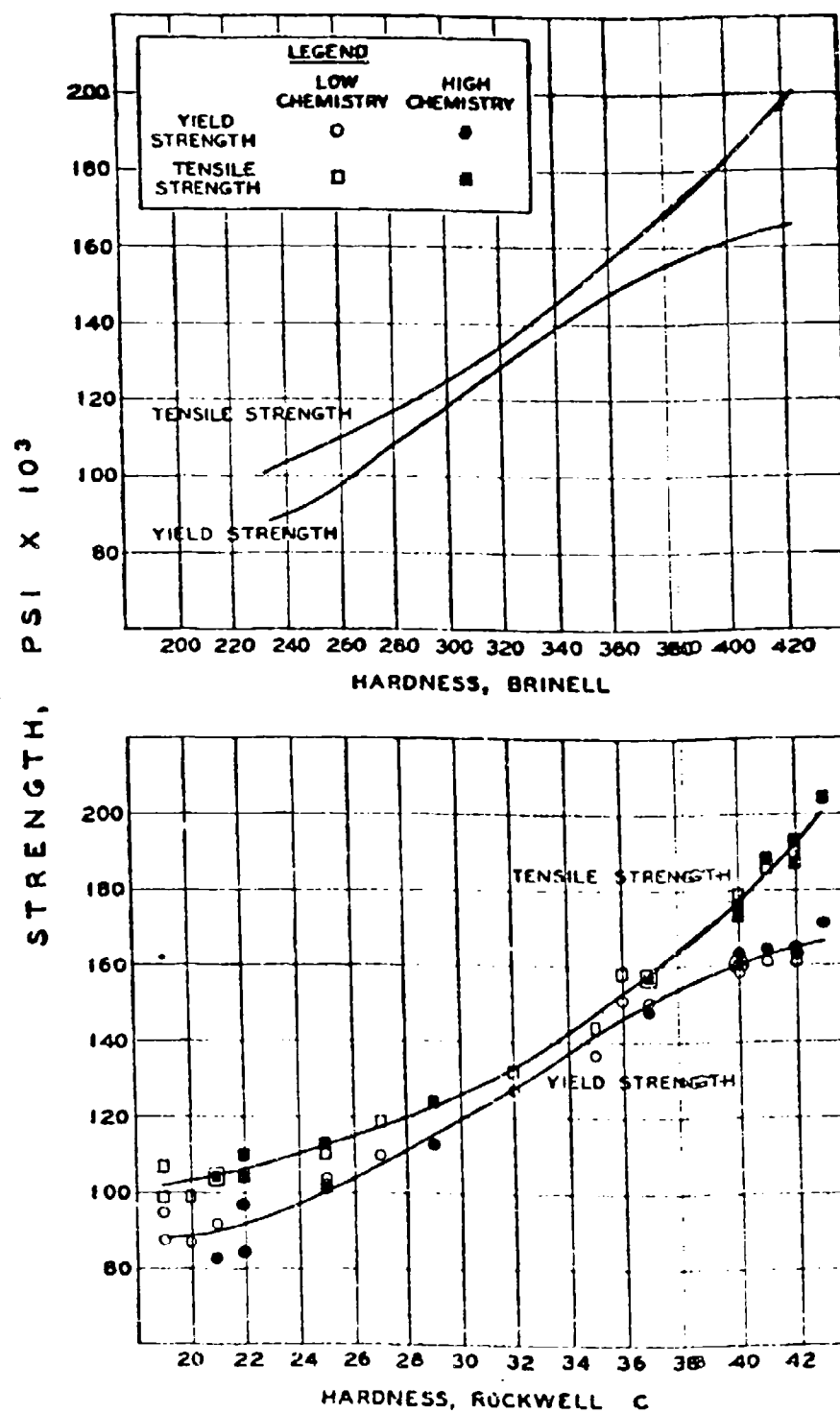


Figure 27 - Relationship between Hardness and Yield and Tensile Strengths for Low- and High-Chemistry HY-80 Steel Austenitized between 1550 and 1650° F

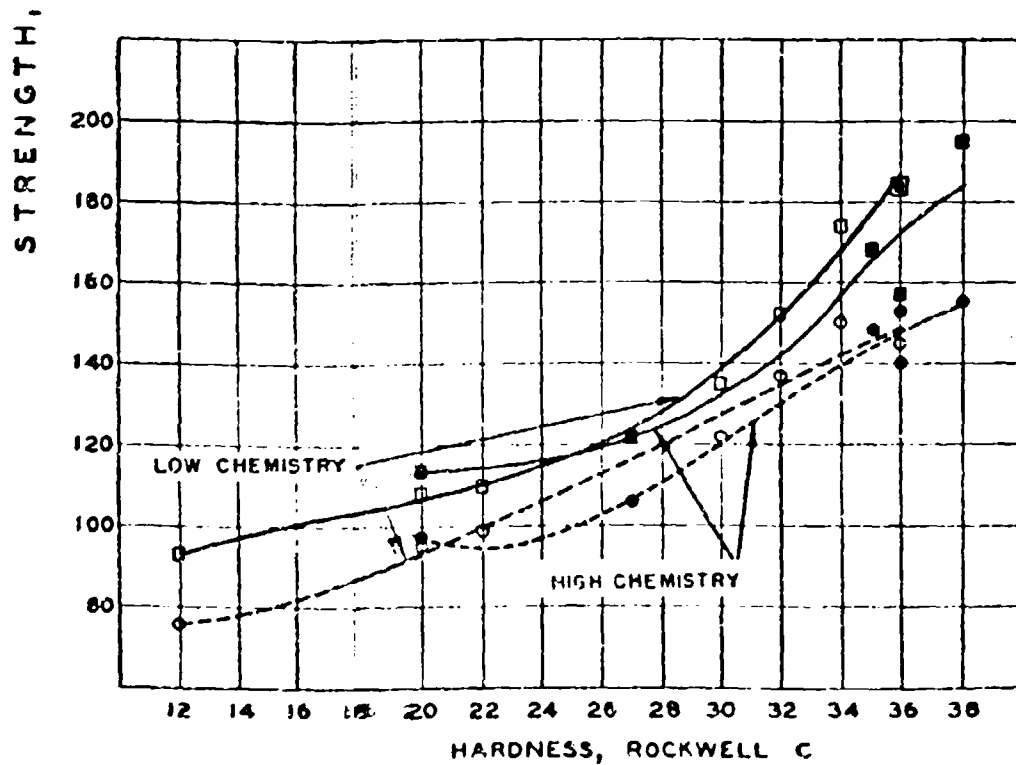
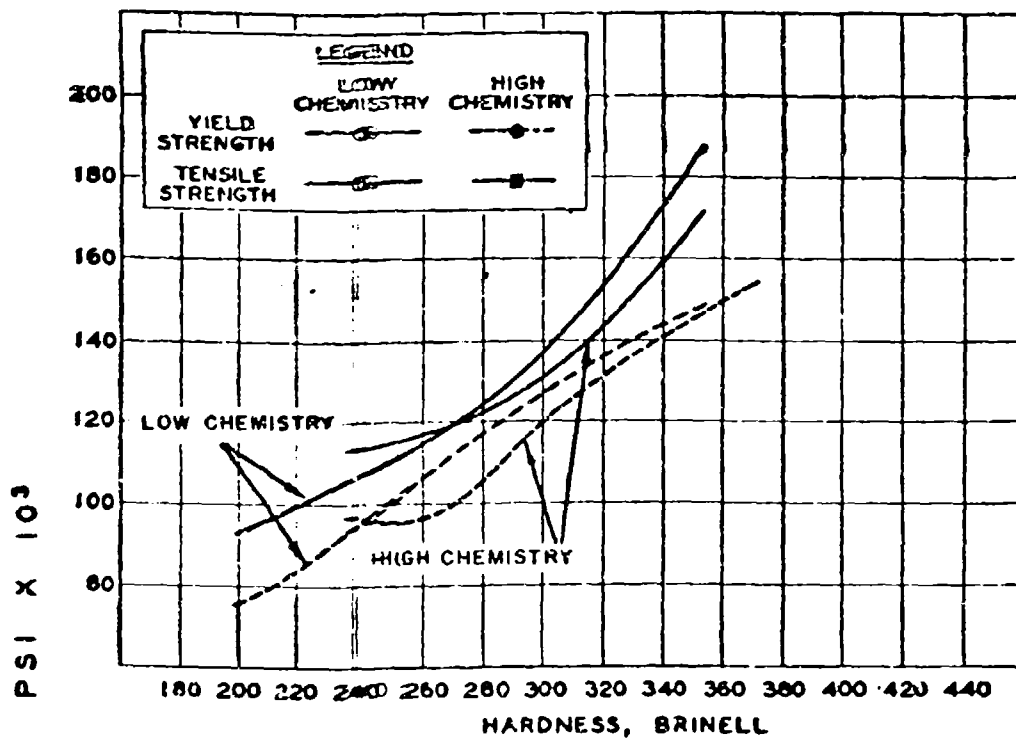


Figure 28 - Relationship between Hardness and Yield and Tensile Strengths for Low- and High-Chemistry HY-80 Steels Austenitized between 1800 and 2000° F

Higher austenitizing temperatures may increase the NDT temperature, that is, the energies obtained for specimens austenitized above 1800° F (while meeting the 50 ft-lb level at -120° F) do not necessarily indicate an acceptable NDT temperature.

In Figures 11 and 15, in which longitudinal and transverse Charpy V-notch curves are compared, the lower legs of the curves do not merge as would normally be expected. It is believed that this failure to merge between the lower plateaus may be due to composition, heat-treatment, and amount of cross-rolling; however, examination of Charpy V-notch curves taken from a number of production-produced plates indicated that this separation is normal for HY-80.

Figure 23 shows that austenitizing temperatures have an effect on the transverse Charpy V-notch fibrous-fracture transition temperatures for a given fibrous fracture. It depicts that, for the high austenitizing temperatures, 1800 to 2000° F, the Charpy V-notch fibrous-fracture transition temperatures are above the transition temperatures obtained from the low austenitizing temperatures, 1550 to 1650° F. The only exception to the preceding observation is the high-chemistry steel tempered at 400° F after quenching from the 2000° F treatment. The higher the strength level, the greater the difference in spread between the high and low austenitizing temperatures.

For the steel chemical compositions investigated, it appears from Tables 5 and 6 that the minimum transition temperature for any given fibrous condition resulted by austenitizing at 1550° F for the low-chemistry and at 1625° F for the high-chemistry HY-80 steels. However, the duplex austenitizing treatments above 1800° F result in higher transition temperatures. For example, it can be seen for the 50-percent fibrous-fracture transition temperature in Tables 5 and 6 and Figure 23 that there is approximately a 100° F difference between duplex high austenitizing treatments and the optimum austenitizing temperatures found, respectively, for the low- and high-chemistry HY-80 steels.

The lowest Charpy V-notch fibrous-fracture transition temperature, 100,000- to 110,000-psi yield, appears to be at 1150 and 1200° F for the 1-hr tempering times as evident by Numbers 6 and 9 in Figure 23, 100,000- to 110,000-psi yield strengths. In fact, in Figure 23 the least-square fit shows that the transition temperatures have a tendency to increase with tempering temperatures above 1200° F and with yield strengths below 100,000 psi.

From Figure 22, it is seen that for any given transverse Charpy V-notch fibrous fracture appearance and for any selected strength level, the energy-absorption level is independent of austenitizing and tempering temperatures. This figure shows that, for Charpy V-notch 80- and 100-percent fibrous fracture appearance and for maximum energy-absorption level, the energies increase with decreasing strength levels. But the Charpy V-notch energy-absorption levels for 50- and 30-percent fibrous fracture appearances show a decrease after 95,000-psi yield strength or after the 110,000-psi-tensile-strength level is reached.

It is interesting to note from Figure 25 that the low-chemistry HY-80 steel, if fully quenched and tempered to a yield strength of 150,000 psi, will have for the 50-percent-fibrous-fracture-transition level, a transverse Charpy V-notch energy absorption of 28 ft-lb at -70° F,

and a corresponding longitudinal Charpy V-notch energy absorption of 42 ft-lb at -80°F . For high-chemistry HY-80 steel heat-treated to a yield strength of 150,000 psi, Figure 22 shows that the transverse Charpy V-notch 50-percent fibrous-fracture energy values would also fall close to the 28 ft-lb level. However, from the black closed triangles for the 50-percent fibrous-fracture-transition temperature in Figure 23, this energy value would be obtained at a test temperature of -95°F . The longitudinal energies for this same fracture criterion probably would be above 45 ft-lb at -110°F .

From the test results of either of the HY-80 chemistries investigated, it can be seen from Tables 5 and 6 and from Figure 23 that the steel is subject to aging in two tempering ranges. For the 500 and 800°F tempers the effect is to increase the transition temperature and strength level. In Figure 25 the longitudinal fibrous-fracture transition temperatures for these same tempering temperatures show the same significant increase. For tempering between 1150 and 1200°F there appears to be a combination of two effects. The first is the precipitation of a complex molybdenum carbide phase, giving rise to a secondary hardening or aging effect,¹⁹ and the second is a softening effect due to the coalescence of carbides in tempering. Because these effects nullify each other, the strength level remains somewhat constant, but the transverse fibrous-fracture transition temperatures are slightly decreased. The longitudinal fibrous transition temperatures show a greater decrease.

Figure 10 depicts the changes in yielding characteristics for various austenitizing treatments. The theoretical aspects of relating discontinuous and continuous yielding to microstructure and its relationship to practical application will be covered in the final report on Phase I. The transverse Charpy V-notch energies would be increased by cross-rolling, but the longitudinal Charpy V-notch energies would be reduced. In any case, the data presented and the relative changes resulting from changing a given heat-treating variable would be applicable for either the straight-away or the cross-rolled plates.

These data are not intended, for the present, to relate brittleness to any of the Navy's established notch tests. Once the effects of all the heat-treating variables on the mechanical properties of HY-80 steel have been established, these data will be related with the drop-weight test in order to define the effects of given variables on the nil-ductility transition temperatures (NDT).

It is emphasized that the data given herein are mainly for the purpose of establishing a baseline for comparing the effects of isothermal products and relating the results of investigations to be conducted in Phases II, III, and IV of this study. As additional data are gathered, they will be used to develop limitations of the preceding correlations.

CONCLUSIONS

It is concluded that the effects of various austenitic and tempering treatments on the mechanical properties of fully quenched HY-80 steel used in this investigation are as follows:

1. Various austenitizing temperatures do not affect the mechanical tensile properties of HY-80 steels quenched after austenitizing and then tempered between 1150 and 1270° F.

2. Transverse Charpy V-notch impact energies are above the 50 ft-lb level at -120° F for specimens quenched from between the austenitizing temperatures of 1550 and 1700° F and tempered between 1150 and 1270° F.

3. Austenitizing between 1800 and 2000° F temperature range increases the transverse Charpy V-notch impact 50-percent fibrous-fracture transition temperature 100° F over the transition temperatures obtained at the lower austenitizing temperature. However, the transverse energy values are above the longitudinal 30 ft-lb requirements of the specification for plates over 61.2 lb per sq ft.

4. Tempering times up to 16 hr have no effect on notch-brittleness properties.

5. A correlation has been established relating strength level to Charpy V-notch energy absorption and transition temperature for four fibrous fracture appearances.

6. A relationship has been developed correlating longitudinal and transverse Charpy V-notch data for a given fibrous fracture appearance.

APPENDIX

LEAST-SQUARE EQUATIONS USED IN CORRELATION OF DATA

In this Appendix the least-square equations and the sigma values developed for the curves of Figures 22, 23, 25, 27, and 28 are given.

The symbols used in the equations given in this Appendix and the meanings of these symbols are:

A. Longitudinal Strength, F

1. F_{1y} is tensile yield strength in kips.
2. F_{1u} is ultimate tensile strength in kips.

B. Transverse Charpy V-Notch Energy Absorbed, E

1. E_{max} is maximum energy absorbed in ft-lb.
2. E_{100} is energy absorbed in ft-lb at 100-percent fibrous fracture appearance.
3. E_{80} is energy absorbed in ft-lb at 80-percent fibrous fracture appearance.
4. E_{50} is energy absorbed in ft-lb at 50-percent fibrous fracture appearance.
5. E_{20} is energy absorbed in ft-lb at 30-percent fibrous fracture appearance.

C. Transverse Charpy V-Notch Fibrous Fracture Transition Temperature, T

1. 100-percent fibrous fracture appearance.
 - a. T_{100-HA} is combined low- and high-chemistry HY-80 steel austenitized 1800 to 2000° F.
 - b. T_{100-LA}^{LC} is low-chemistry HY-80 steel austenitized 1550 to 1650° F.
 - c. T_{100-LA}^{HC} is high-chemistry HY-80 steel austenitized 1550 to 1650° F.
2. 80-percent fibrous fracture appearance.
 - a. T_{80-HA} is combined low- and high-chemistry HY-80 steel austenitized 1800 to 2000° F.
 - b. T_{80-LA}^{LC} is low-chemistry HY-80 steel austenitized 1550 to 1650° F.
 - c. T_{80-LA}^{HC} is high-chemistry HY-80 steel austenitized 1550 to 1650° F.
3. 50-percent fibrous fracture appearance
 - a. T_{50-HA} is combined low- and high-chemistry HY-80 steel austenitized 1800 to 2000° F.
 - b. T_{50-LA} is combined low- and high-chemistry HY-80 steel austenitized 1550 to 1650° F.

4. 30-percent fibrous fracture appearance

a. T_{30-HA} is combined low- and high-chemistry HY-80 steel austenitized 1800 to 2000° F.

b. T_{30-LA} is combined low- and high-chemistry HY-80 steel austenitized 1550 to 1650° F.

D. Directional Charpy V-Notch Impact Properties

1. Longitudinal

a. E_L is energy absorbed in ft-lb.

b. T_L is fibrous transition temperature in deg F.

2. Transverse

a. E_T is energy absorbed in ft-lb.

b. T_T is fibrous transition temperature in deg F.

To correlate longitudinal strength and transverse Charpy V-notch energy absorbed at maximum energy absorbed and at a given fibrous fracture appearance (Figure 22), the following equations and sigma values were used:

A. Maximum Energy Absorbed

1. Yield Strength

$$E_{max} = -269 + 10.450 (F_{ty}) - 0.09426 (F_{ty})^2 + 2.5513 (F_{ty})^3 \times 10^{-4}; \sigma = 5 \text{ ft-lb}$$

2. Tensile Strength

$$E_{max} = 10.38 + 3.424 (F_{tu}) - 0.03465 (F_{tu})^2 + 9.0726 (F_{tu})^3 \times 10^{-5}; \sigma = 5 \text{ ft-lb}$$

B. 100-Percent Fibrous Fracture Appearance

1. Yield Strength

$$E_{100} = -199 + 8.6097 (F_{ty}) - 0.07959 (F_{ty})^2 + 2.1777 (F_{ty})^3 \times 10^{-4}; \sigma = 4 \text{ ft-lb}$$

2. Tensile Strength

$$E_{100} = 83.33 + 1.755 (F_{tu}) - 0.02303 (F_{tu})^2 + 6.4990 (F_{tu})^3 \times 10^{-5}; \sigma = 5 \text{ ft-lb}$$

C. 80-Percent Fibrous Fracture Appearance

1. Yield Strength

$$E_{80} = 11.9 + 2.810 (F_{ty}) - 0.03157 (F_{ty})^2 + 9.2330 (F_{ty})^3 \times 10^{-5}; \sigma = 5 \text{ ft-lb}$$

2. Tensile Strength

$$E_{80} = 192.68 - 1.157 (F_{tu}) - 0.001001 (F_{tu})^2 + 1.3663 (F_{tu})^3 \times 10^{-5}; \sigma = 4 \text{ ft-lb}$$

D. 50-Percent Fibrous Fracture Appearance

1. Yield Strength

$$E_{50} = -282 + 8.510 (F_{ty}) - 0.07020 (F_{ty})^2 + 1.8210 (F_{ty})^3 \times 10^{-4}; \sigma = 3 \text{ ft-lb}$$

2. Tensile Strength

$$E_{50} = -136.42 + 4.408 (F_{tu}) - 0.03325 (F_{tu})^2 + 7.6860 (F_{tu})^3 \times 10^{-5}; \sigma = 3 \text{ ft-lb}$$

E. 30-Percent Fibrous Fracture Appearance

1. Yield Strength

$$E_{30} = -188 + 5.7002 (F_{ty}) - 0.04664 (F_{ty})^2 + 1.2130 (F_{ty})^3 \times 10^{-4}; \sigma = 4 \text{ ft-lb}$$

2. Tensile Strength

$$E_{30} = -138.22 + 3.836 (F_{tu}) - 0.02723 (F_{tu})^2 + 6.1028 (F_{tu})^3 \times 10^{-5}; \sigma = 4 \text{ ft-lb}$$

To correlate longitudinal strength and transverse Charpy V-notch fibrous fracture transition temperatures (Figure 23) the following equations and sigma values were used:

A. 100-Percent Fibrous Fracture Appearance

1. Austenitized 1800 to 2000° F, Low- and High-Chemistry HY-80 Steel

a. Yield Strength

$$T_{100-HA} = 1.834 - 50.120 (F_{ty}) + 0.43311 (F_{ty})^2 - 1.1567 (F_{ty})^3 \times 10^{-3}; \sigma = 23^\circ \text{ F}$$

b. Tensile Strength

$$T_{100-HA} = 822 - 21.284 (F_{tu}) + 0.16738 (F_{tu})^2 - 3.8475 (F_{tu})^3 \times 10^{-4}; \sigma = 18^\circ \text{ F}$$

2. Austenitized 1550 to 1650° F

a. Low-Chemistry HY-80 Steel

(1) Yield Strength

$$T_{100-LA}^{LC} = 202.3 - 6.410 (F_{ty}) + 0.034544 (F_{ty})^2; \sigma = 17^\circ \text{ F}$$

(2) Tensile Strength

$$T_{100-LA}^{LC} = -44.4 - 2.2231 (F_{tu}) + 0.01750 (F_{tu})^2 - 8.9110 (F_{tu})^3 \times 10^{-6}; \sigma = 16^\circ \text{ F}$$

b. High-Chemistry HY-80 Steel

(1) Yield Strength

$$T_{100-LA}^{HC} = -13.47 - 1.4926 (F_{ty}) - 3.8195 (F_{ty})^2 + 7.7435 (F_{ty})^3 \times 10^{-5}; \sigma = 5^\circ \text{ F}$$

(2) Tensile Strength

$$T_{100-LA}^{HC} = 687 - 22.024 (F_{tu}) + 0.15202 (F_{tu})^2 - 3.2131 (F_{tu})^3 \times 10^{-4}; \sigma = 2^\circ \text{ F}$$

B. 80-Percent Fibrous Fracture Appearance

1. Austenitized 1600 to 2000° F, Low- and High-Chemistry HY-80 Steel

a. Yield Strength

$$T_{80-HA} = -1995 + 46.226 (F_{ty}) - 0.37076 (F_{ty})^2 + 1.03942 (F_{ty})^3 \times 10^{-3}; \sigma = 10^\circ \text{ F}$$

b. Tensile Strength

$$T_{80-HA} = -48 - 4.7697 (F_{tu}) + 0.05993 (F_{tu})^2 - 1.5728 (F_{tu})^3 \times 10^{-4}; \sigma = 7^\circ \text{ F}$$

2. Austenitized 1550 to 1650° F

a. Low-Chemistry HY-80 Steel

(1) Yield Strength

$$T_{80-LA}^{LC} = -295 + 5.4574 (F_{ty}) - 0.06754 (F_{ty})^2 + 2.8880 (F_{ty})^3 \times 10^{-4}; \sigma = 14^\circ \text{ F}$$

(2) Tensile Strength

$$T_{80-LA}^{LC} = 1025 - 27.371 (F_{tu}) + 0.20215 (F_{tu})^2 - 4.4890 (F_{tu})^3 \times 10^{-4}; \sigma = 15^\circ \text{ F}$$

b. High-Chemistry HY-80 Steel

(1) Yield Strength

$$T_{80-LA}^{HC} = 668 - 24.121 (F_{ty}) + 0.17792 (F_{ty})^2 - 3.9476 (F_{ty})^3 \times 10^{-4}; \sigma = 3^\circ \text{ F}$$

(2) Tensile Strength

$$T_{80-LA}^{HC} = 2523 - 57.598 (F_{tu}) + 0.39925 (F_{tu})^2 - 8.8019 (F_{tu})^3 \times 10^{-4}; \sigma = 2^\circ \text{ F}$$

C. 50-Percent Fibrous Fracture Appearance

1. Austenitized 1800 to 2000° F, Low- and High-Chemistry HY-80 Steel

a. Yield Strength

$$T_{50-HA} = 1082 - 31.830 (F_{iy}) + 0.26820 (F_{iy})^2 - 6.7457 (F_{iy})^3 \times 10^{-4}; \sigma = 10^\circ \text{ F}$$

b. Tensile Strength

$$T_{50-HA} = 1452 - 37.380 (F_{iu}) + 0.28467 (F_{iu})^2 - 6.6366 (F_{iu})^3 \times 10^{-4}; \sigma = 12^\circ \text{ F}$$

2. Austenitized 1550 to 1650° F, Low- and High-Chemistry HY-80 Steel

a. Yield Strength

$$T_{50-LA} = 959 - 28.54 (F_{iy}) + 0.22706 (F_{iy})^2 - 5.4845 (F_{iy})^3 \times 10^{-4}; \sigma = 14^\circ \text{ F}$$

b. Tensile Strength

$$T_{50-LA} = 1658 - 41.838 (F_{iu}) + 0.30632 (F_{iu})^2 - 7.0058 (F_{iu})^3 \times 10^{-4}; \sigma = 13^\circ \text{ F}$$

D. 30-Percent Fibrous Fracture Appearance

1. Austenitized 1800 to 2000° F, Low- and High-Chemistry HY-80 Steel

a. Yield Strength

$$T_{30-HA} = 597 - 20.990 (F_{iy}) + 0.18024 (F_{iy})^2 - 4.3766 (F_{iy})^3 \times 10^{-4}; \sigma = 11^\circ \text{ F}$$

b. Tensile Strength

$$T_{30-HA} = 1292 - 34.636 (F_{iu}) + 0.2633 (F_{iu})^2 - 6.0891 (F_{iu})^3 \times 10^{-4}; \sigma = 13^\circ \text{ F}$$

2. Austenitized 1550 to 1650° F, Low- and High-Chemistry HY-80 Steel

a. Yield Strength

$$T_{30-LA} = 827 - 26.548 (F_{iy}) + 0.21465 (F_{iy})^2 - 5.26397 (F_{iy})^3 \times 10^{-4}; \sigma = 15^\circ \text{ F}$$

b. Tensile Strength

$$T_{30-LA} = 2136 - 53.379 (F_{iu}) + 0.39093 (F_{iu})^2 - 9.0322 (F_{iu})^3 \times 10^{-4}; \sigma = 18^\circ \text{ F}$$

To correlate transverse and longitudinal Charpy V-notch impact properties (energy absorbed and fibrous-fracture transition temperature) for maximum energy and for any given percent fibrous fracture appearance of a fully quenched, production-rolled low-chemistry HY-80 steel plate (Figure 26), the following equations and sigma values were used:

A. Transverse Energy Absorbed versus Longitudinal Energy Absorbed

$$E_L = -10.4 + 2.069 (E_T) - 5.2107 (E_T)^2 \times 10^{-3}; \sigma = 7 \text{ ft-lb}$$

B. Transverse Transition Temperature versus Longitudinal Transition Temperature

$$T_L = -13.6 + 1.025 (T_T) - 6.5633 (T_T)^2 \times 10^{-4}; \sigma = 25^\circ \text{ F}$$

To correlate hardness, Rockwell C scale, and longitudinal strengths for HY-80 steel austenitized between 1550 and 1650° F, Figure 27, the following equations and sigma values were used:

A. Yield Strength

$$F_{iy} = 249.4 - 20.101 (R_C) + 0.76245 (R_C)^2 - 7.8967 (R_C)^3 \times 10^{-3}; \sigma = 3.5 \text{ kips}$$

B. Tensile Strength

$$F_{ts} = 67.9 + 3.166 (R_C) - 0.13063 (R_C)^2 + 2.9952 (R_C)^3 \times 10^{-3}; \sigma = 2.8 \text{ kips}$$

To correlate hardness, Rockwell C scale, and longitudinal strength for HY-80 steel austenitized between 1800 and 2000° F, Figure 28, the following equations and sigma values were used:

A. Low-Chemistry HY-80 Steel

1. Yield Strength

$$F_{iy}^{LC} = 87.4 - 3.394 (R_C) + 0.23716 (R_C)^2 - 2.6404 (R_C)^3 \times 10^{-3}; \sigma = 4.1 \text{ kips}$$

2. Tensile Strength

$$F_{ts}^{LC} = 26.1 + 10.173 (R_C) - 0.49279 (R_C)^2 + 9.2964 (R_C)^3 \times 10^{-3}; \sigma = 3.1 \text{ kips}$$

B. High-Chemistry HY-80 Steel

1. Yield Strength

$$F_{iy}^{HC} = 605.8 - 56.96 (R_C) + 2.0093 (R_C)^2 - 0.02166182 (R_C)^3 \times 10^{-3}; \sigma = 4.2 \text{ kips}$$

2. Tensile Strength

$$F_{ts}^{HC} = 70.6 + 7.605 (R_C) - 0.44659 (R_C)^2 + 8.73005 (R_C)^3 \times 10^{-3}; \sigma = 8.1 \text{ kips}$$

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